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Rb–Sr Geochronology of Middle Riphean Shales, the Yusmastakh Formation of the Anabar Massif, Northern Siberia

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Abstract—Isotopic dates for upper horizons in one of the Riphean reference sections of northern Eurasia are calculated on the basis of the Rb–Sr systematics of fine size-variable subfractions (SF) of clay minerals. The SFs with particle size ranges <0.1, 0.1–0.2, 0.2–0.3, 0.3–0.6, 0.6–1, 1–2, and 2–5 μm are separated out of two shale samples characterizing the lower and upper Yusmastakh subformations. Clay mineral in all the SFs is the low-temperature illite; feldspar and quartz admixture was detected in the coarsest SFs only. The established crystallinity index standard (CIS) of illite corresponds to that characterizing the diagenesis zone. Leaching in 1N NH_4OAc solution and subsequent Rb–Sr analysis of untreated SFs, leachates and residues offered an opportunity to plot the "inner Rb–Sr isochron" for each SF and to determine its apparent age and initial $^{87}Sr/^{86}Sr$ ratio. In series of SFs arranged according to their size range decrease from 2–5 to <0.1 μm, the following parallel changes of various parameters are established: (1) CIS values and I_{002}/I_{001} ratios increase; (2) Rb and Sr concentrations and $^{87}Sr/^{86}Sr$ ratios grow; (3) $^{87}Rb/^{86}Sr$ ratios in leachates go up; (4) the apparent Rb–Sr age decreases from 1272–1284 down to 1004–1048 Ma. For each sample, data points characterizing leachates and residues of size-variable SFs plot along mixing lines in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ graphs. The XRD analysis and isotopic data show that SFs include three generations of authigenic illite. The considered paleontological, chemostratigraphic, and isotopic-geochronological data clarify age of the Yusmastakh Formation and show that the burial diagenesis affected the corresponding deposits 1280–1270 Ma ago (age of the first illite generation). The subsequent uprising and renewed interstitial fluids initiated two stages of regressive catagenesis 1090–1130 and 1000–1060 Ma ago, when new generations of authigenic illite originated in the Yusmastakh deposits.

Key words: *Proterozoic, Riphean, shales, fine-grained clay fractions, illite, illite crystallinity index, diagenesis, regressive catagenesis, Rb–Sr age, systematics of mixing, leaching, northern Siberia.*

INTRODUCTION

The Riphean sedimentary succession exposed along the Kotuikan River in the western slope of the Anabar massif (Fig. 1) is considered as reference one in northern Eurasia. Along with others, it was recurrently studied in order to elucidate and refine the stratigraphic potential of Proterozoic stromatolites (Komar, 1966; Golovanov, 1970; Shpunt *et al.*, 1982). Data on diverse Late Precambrian organic-walled and silicified microfossils distinguished in this section are used as a basis for the current models of their time-and-space distribution (Golovenok and Belova, 1984; Yakshin, 1986, 1991; Veis and Vorob'eva, 1992; Veis and Petrov, 1994; Sergeev *et al.*, 1995). In Russia, the groundwork for the C- and Sr-isotope chemostratigraphy of the Riphean was also elaborated in this very region (Pokrovskii and Vinogradov, 1991; Knoll *et al.*, 1995). At the same time, the time range of the Kotuikan section is disputable so far, and relevant isotopic-geochronological information is limited by some K–Ar dates for glauconites unstudied in mineralogical aspect. These dates represent a regular series of values changing from 1480–1500 Ma near the base to 1070–1120 Ma in the upper part of the succession (Shpunt *et al.*, 1982; Semikhatov and Serebryakov, 1983, and references therein). More confident Rb–Sr isochron dates were obtained, using the modern approach, not long ago for the density- and/or size-discriminated fractions of authigenic globular and fine-dispersed silicates, which can be attributed to concrete stages of lithogenesis, but they characterize only the Lower Riphean horizons of the Anabar massif (Gorokhov *et al.*, 1991, 1997).

Our main objective in this work is to fill the lacuna in geochronology of upper horizons of the Kotuikan section by means of the Rb–Sr isochron dating of fine size-variable subfractions of authigenic illite. As it turned out, the proper approach to the problem should include consideration of additional broad problems: the

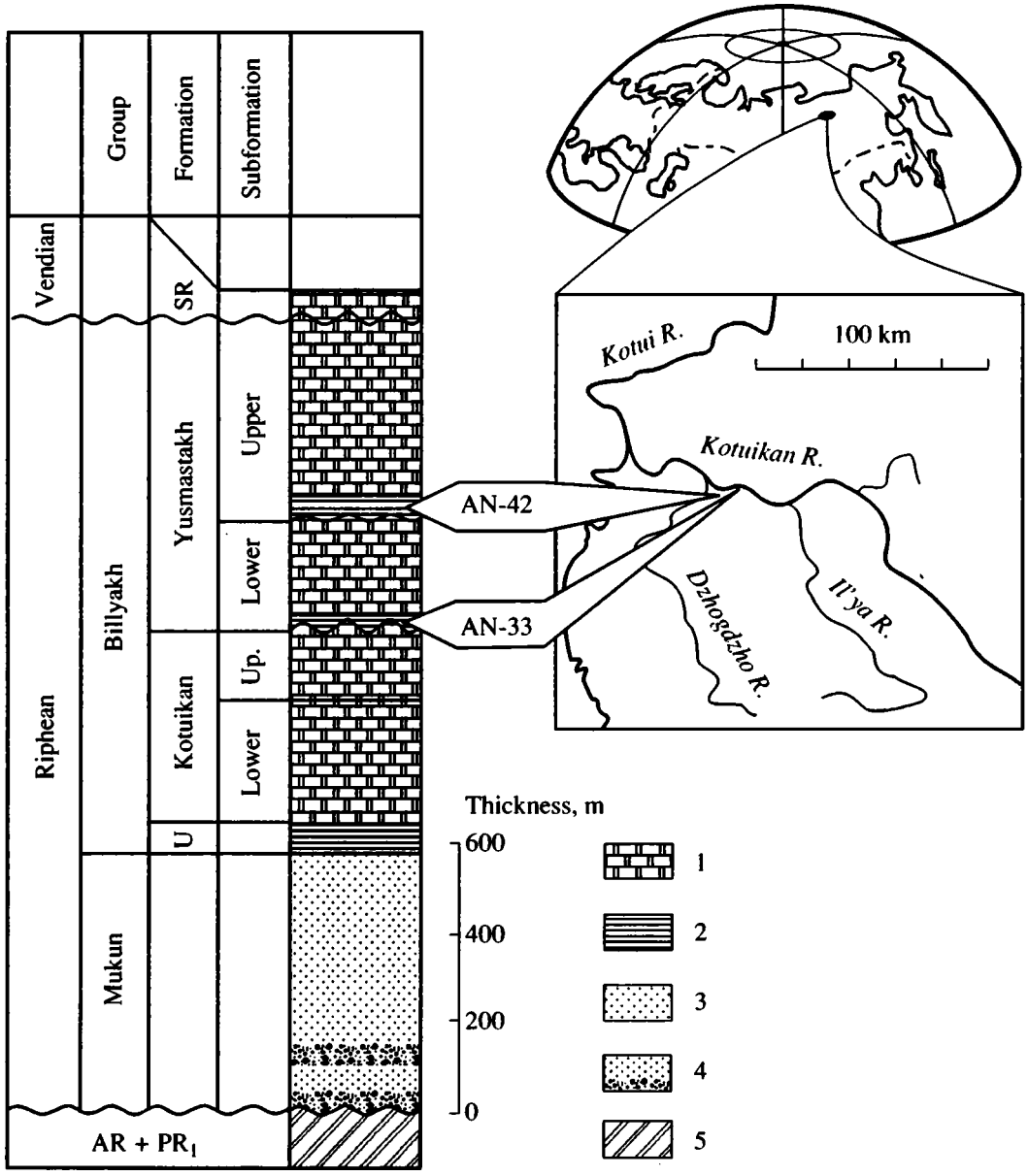

Fig. 1. Lithostratigraphic column of Riphean deposits in the Anabar massif with indicated positions of studied samples: (1) dolomite; (2) shale; (3) siltstone, fine-grained sandstone; (4) sandstone with gravelstone lentils; (5) pre-Riphean crystalline basement; (U) Ust'-Il'ya Formation; (SR) Staraya Rechka Formation.

Rb–Sr systematics of two-component mixing and legitimacy of "inner Rb–Sr isochrons" (leachochons) plotted for leaching products of subfractions.

It is absolutely unnecessary to prove at present that any unmetamorphosed clayey rock represents a mixture of detrital and non-cogenetic authigenic minerals, which retain (or could retain, at least) the isotopic memory of various events that happened during lithogenesis (Clauer, 1976; Bonhomme, 1982; Gorokhov *et al.*, 1984; Morton, 1985; Lander *et al.*, 1991; Lanson and Besson, 1992; Gorokhov *et al.*, 1994; Clauer and Chaudhuri, 1995; Gorokhov, 1996). In general, the isotopic dating of clay fractions with particle size <5 (<2) μm, setting aside the whole-rock shale sample, leads to the meaningless age determinations (Gorokhov and Semikhatov, 1984; Gorokhov and Mel'nikov, 1997; Rublev, 1998, and references therein). To find the way out of the situation, one should divide the common clay fraction (<5 μm) into several subfractions (SF) of a narrow size range (from less than 0.1 to 1–2 μm). After the mineral identification and isotopic dating of each SF, geological meanings of the obtained age values should be interpreted using all data, which can help to elucidate the primary time of sediment accumulation, as

well as the time ranges and intensities of subsequent mineral transformations.

Perspectives of using these SFs in practice of geochronological works were demonstrated in a series of publications (Clauer, 1984; Morton, 1985; Bonhomme, 1987; Clauer *et al.*, 1990; Gorokhov *et al.*, 1994, 1997; Gorokhov, 1996; Gorokhov and Mel'nikov, 1997). On the basis of Lower Riphean to Devonian rocks, it was shown in these publications that different clayey rocks (soaking clay, shale, and argillite) include not one, but two or even three polymorphic modifications of finely dispersed illite ($2M_1$, 1M, and/or 1Md). One of the modifications ($2M_1$) is detrital and may bear information about the provenance age, whereas others originate at different stages of lithogenesis. Our experience with this approach to practical geochronology stimulated this study on illite from shales of the Yusmastakh Formation that constitutes upper horizons of the Riphean in the Kotuikan section of northern Siberia. The studied samples were collected by Semikhatov in 1992.

GEOLOGICAL STRUCTURE AND AGE OF RIPHEAN DEPOSITS IN THE WESTERN SLOPE OF THE ANABAR MASSIF

In the western slope of the Anabar massif, the Riphean deposits occur as a succession of homoclinal strata dipping very gently (2–5°) to the west and locally disturbed by normal faults of minor amplitude. There is a distinct discordance between these and Archean to Lower Proterozoic crystalline rocks exposed within the Anabar massif arch. The Vendian strata (more precisely, Upper Vendian; Kaufman *et al.*, 1996), which overlap the pre-Riphean basement in southern and northern slopes of the massif, unconformably rest on the Riphean deposits (Fig. 1). Distinguished among the latter (Savitskii *et al.*, 1959; Komar, 1966; Zlobin and Golovanov, 1970) are the Mukun Group of siliciclastic rocks (600–650 m) and predominantly carbonate Billyakh Group (900–1100 m) overlying the former. The Billyakh Group includes the Ust'-Il'ya (55–65 m), Kotuikan (250–320 m), and Yusmastakh (650–830 m) formations (Savitskii *et al.*, 1959; Komar, 1966; Zlobin and Golovanov, 1970). The last two subdivisions have been considered once as complex units divisible into subordinate formations (Zlobin and Golovanov, 1970; Serebryakov, 1975).

The Yusmastakh Formation, from which the studied samples are collected, is separated from the Kotuikan Formation by the erosion surface displaying indications of incipient karstification. Its lower subformation (200–230 m) begins with the 5.5- to 6-m-thick member, where clastic dolomites (dolarenites and dololutites) are intercalated with microbialites and shales; in the lower part of the member, there are additional silty to sandy intercalations. One of the studied samples (AN-33) was collected from an interlayer of bluish gray homogeneous shale (30 cm thick) that is exposed within the member at the right side of the Kotuikan River, 2.1 km upstream of the Nekyuleekh Creek. The greater overlying part of the lower Yusmastakh Subformation is composed of alternating stromatolitic, oolitic, clastic, and micritic dolomites, dolomitic marls, and sporadic shales. The upper subformation (450–500 m) resting again on the karstified erosion surface differs from the lower one owing to the presence of small (2–4 m thick) transgressive rhythms, and, in addition, the stromatolitic dolomites are slightly more abundant here. At the base of this subformation, there is the 8- to 10-m-thick member, where clastic and laminated microbial dolomites alternate with bluish dolomitic shales, or with glauconite siltstones and occasional sandstones concentrated in its basal interval. The second studied sample (AN-42) was collected at the left side of the Kotuikan River, 2.5 km upstream of the Dzhogdzho River mouth, from the carbonate-free shale interlayer in the middle part of the member. Carbonate rocks of the Yusmastakh Formation accumulated mostly in upper subtidal to intertidal settings with active hydrodynamics. Frequent events of subaerial exposing are recorded in these rocks as recurring surfaces with erosion marks and desiccation cracks. The marker horizon of stromatolitic dolomite near the base of the upper subformation and the basal units of each subformation, which show alternation of clayey and carbonate rocks, were deposited in more stable settings of the upper subtidal zone. These units point to a quick flooding of former erosion surfaces and subsequent sedimentation near or below the fair weather wave base.

The time range of the Yusmastakh Formation is inferable from a set of isotopic-geochronological, chemostratigraphic, and paleontological data, interpretation of which in current publications is still ambiguous. In the Anabar massif, the entire Riphean succession is obviously younger than magmatic series that originated by collision of the Early Proterozoic terranes at the formation stage of the pre-Riphean basement in this region of the Siberian platform (Rozen *et al.*, 2000). The U–Pb zircon age of youngest rocks from these series ranges from 1843 ± 12 to 1760 ± 20 Ma (Stepanyuk, 1974, 1991), and K–Ar dates for micas from the same rocks correspond to 1800–1810 Ma in general (*Geokhronologiya...*, 1968). On the other hand, data of isotopic geochronology show that basal horizons of the upper Yusmastakh Subformation are not younger than 1070–1120 Ma (K–Ar dates for mineralogically unstudied glauconites from this level; *Geokhronologiya...*, 1968) while eight density fractions of glauconite from the Ust'-Il'ya Formation define the Rb–Sr isochron age equal to 1483 ± 5 Ma, and the average K–Ar age estimated for these fractions is 1459 ± 10 Ma (Gorokhov *et al.*, 1991). Two last dates are interpreted as defining time of the early diagenesis of the Ust'-Il'ya sediments, because the Mössbauer spectrum of studied glauconites suggests that the Rb–Sr and K–Ar isotopic-geochronological systems are undisturbed in these minerals. The above interpretation was proved later on, after the Rb–Sr isotopic analysis of

size-variable subfractions of authigenic illite from the same sediments, origin of which is attributed to the stage of burial diagenesis that happened, as estimated, 1415–1405 Ma ago (Gorokhov *et al.*, 1997).

In carbonates of the Billyakh Group, $\delta^{13}C$ values are fairly uniform, ranging from –1.6 to +0.4‰ PDB in unaltered rock samples (Pokrovskii and Vinogradov, 1991; Knoll *et al.*, 1995). Interpreting these isotopic data in terms of chemostratigraphy, Knoll *et al.* (1995) and Semikhatov (1995) concluded that the Billyakh Group is older than the Upper Precambrian deposits of the Turukhansk region. The latter belong to the Middle–Upper Riphean transition level (about 1100–850 Ma), and their carbonates reveal, in general, the more contrast but relatively low positive values of $\delta^{13}C$. Judging from the established global trend of $\delta^{13}C$ variations during the Riphean, one can state that the Billyakh Group is not younger than 1250–1270 Ma, because the change-over in $\delta^{13}C$ values from 0 ± 1‰ PDB (the range typical of the Lower–basal Middle Riphean) to +2 or +3‰ PDB (values characteristic of the upper Middle Riphean rocks) is recorded exactly at that level (Kah *et al.*, 1999; Bartley *et al.*, in press). At the same time, there is an alternative viewpoint based on the model of Sr isotope variations in Proterozoic oceans that was suggested by Veizer and Compston (1976). Vinogradov and his colleagues (Pokrovskii and Vinogradov, 1991; Vinogradov *et al.*, 1994), the orthodox adherents of the model, believe that the Billyakh group should be attributed to the Lower Riphean, or even to the Lower Proterozoic, since the initial $^{87}Sr/^{86}Sr$ ratios in carbonates of the group are as low (0.70480–0.70509) as those characterizing, according to that model, the pre-Riphean interval of isotopic records. Their conclusion contradicts, however, not only the aforementioned isotopic dates obtained for the youngest pre-Riphean granites and basal horizons of the group, but also the recent data on variations of $^{87}Sr/^{86}Sr$ ratios in the Lower Proterozoic and Lower–Middle Riphean carbonates (Veizer *et al.*, 1992; Gorokhov *et al.*, 1995; Bartley *et al.*, in press, and references therein). According to these data, the Sr isotope composition in the Billyakh carbonates may indicate that the group in question is younger than 1625–1690 Ma, but older than 1100–1150 Ma.

Paleontological characteristics of deposits under consideration are diverse. Organic remains are scarce in the Mukun Group, but two lower formations of the Billyakh Group are fossiliferous and yield diverse assemblages of organic-walled microfossils, among them the relatively large forms of a complex morphology, e.g., *Chuaria, Simia, Ostiana, Polytrichoides, Rectia, Asperatofyllum, Caudosphaera*, large branching thalluses, and others (Veis and Vorob'eva, 1992). In some publications (op. cit. Veis and Petrov, 1994; Veis *et al.*, 2000), they have been considered as characteristic representatives of the Late Riphean microbiota, whereas other researchers (Sergeev *et al.*, 1995) suspect the Early–Middle Riphean age of these and associated silicified microfossils. We argue against the first opinion because of two reasons. First, the suggested Late Riphean age of organic-walled microfossils from the lower Billyakh deposits is incompatible with isotopic dates characterizing these and other Siberian deposits, which yield similar organic remains (see Semikhatov, 1995). Second, almost all characteristic representatives of the microbiota in question were recently discovered in the undoubtedly pre-Upper Riphean deposits of European Russia (Veis *et al.*, 2000), namely in the Middle Riphean succession of the southern Urals and in the Lower Riphean strata of the Volga–Urals region.

Stromatolites of the Mukun Group are mainly represented by North Siberian endemic forms, which associate, however, with some stratigraphically important interregional taxa (Komar, 1966; Golovanov, 1970; Shpunt *et al.*, 1982; Shenfil', 1991). For instance, *Kussiella kussiensis* Kryl., a common form in the lower Kotuikan Subformation, is considered as the typical Lower Riphean species in northern Eurasia, though its occurrences are known as well in the terminal Lower Proterozoic and, occasionally, in the Middle Riphean (Semikhatov and Serebryakov, 1983; Walter *et al.*, 1988). In addition to local representatives of characteristic Middle Riphean form genera *Baicalia* and *Svetliella*, the basal portion of the Yusmastakh Formation yields *Conophyton metula* Kir. that is typomorphic of the Middle and lower Upper Riphean. In accordance with appearance of the last taxa, the Lower–Middle Riphean boundary is placed in the Kotuikan section at the base of the Yusmastakh Formation (Semikhatov and Serebryakov, 1983; Shenfil', 1991; Sergeev *et al.*, 1995, and references therein). Taxonomic composition of silicified microfossils from the Yusmastakh Formation neither contradicts, nor proves the last conclusion (Sergeev *et al.*, 1995). Organic-walled microfossils have not been discovered so far in the Yusmastakh Formation.

Among stromatolites occurring in the uppermost Yusmastakh beds, there are endemic representatives of two form genera, one of which (*Gymnosolen*) is widespread in the Upper Riphean of northern Eurasia, and another (*Boxonia*) is known from Vendian deposits. Appearance of both indicated taxa was traditionally considered as argument in favor of the Late Riphean age of their host sediments (op. cit.). In view of their endemism and, primarily, from the viewpoint of chemostratigraphic data discussed above, this argument cannot be regarded now as convincing.

Thus, the available isotopic-geochronological and chemostratigraphic data suggest that the Yusmastakh Formation is younger than 1460–1480 Ma, but older than 1250–1270 Ma, and paleontological considerations imply correspondence of its lower part with the Middle Riphean. Taking into account these assessments and the accepted isotopic age of the Lower–Middle Riphean boundary (1350 ± 20 Ma; Semikhatov *et al.*,

1991), we conclude that age limits of the Yusmastakh Formation cannot be beyond 1250–1350 Ma.

INVESTIGATION PROCEDURES

Two rock samples used for isotopic dating of the Yusmastakh deposits are homogeneous outwardly, taken from the relatively thick (>20 cm) shale interlayers, and visually lacking silty, sandy, or carbonate admixture. The laboratory treatment of these samples (AN-33 from lower and AN-42 from upper subformations) included three stages: (1) separation of fine size-variable illite subfractions, each subjected afterward to X-ray spectroscopy in order to identify their mineral composition, as well as the polytypy and crystallinity index of illite; (2) leaching of each subfraction in ammonium acetate; (3) Rb–Sr isotopic analysis.

Fractionation and XRD analysis. Samples preliminary cleaned of external weathering products were carefully powdered with the help of hand-power press and recurrent sieving that removed size fraction <0.25 mm. Then, by means of elutriation in the distilled water in accord with the Stokes' law, size fractions <5 and <2 μm were separated from samples AN-33 and AN-42, respectively. Afterward, using centrifuging and ultrafiltration, we divided them into granulometric subfractions equivalent to spherical particles <0.1, 0.1–0.2, 0.2–0.3, 0.3–0.6, 0.6–2 (0.6–1 and 1–2), and 2–5 μm in diameter. The separated SFs were not greater than 1 g in weight that did not guarantee sometimes the homogeneity of clay substance. The duplicate analyses of aliquots were therefore not always reproducible.

Diffractometer DRON UM-1 with COK_α-emission was used to perform the XRD analysis. We tend to keep the slide thickness approximately constant for all SFs. X-ray diffractograms of nonoriented slides were used to determine the illite polytypy, and those of oriented slides allowed us to calculate the crystallinity index (CIS) of this mineral. The last parameter I_k (Kubler, 1966, 1990) characterizes the half-height width of 10 Å-peak of illite measured in degrees of arc (Kisch, 1980). In order to unify the crystallinity index values, Warr and Rice (1994) suggested to use the interlaboratory standards, which can be prepared in any laboratory and subsequently used for calibration of customary measurements. We accepted the recommended procedure and recalculated our measurement results into the CIS values using the following equation:

$$CIS = (1.66 \pm 0.08)I_k - (0.02 \pm 0.02).$$

Leaching. The radiogenic ^{87}Sr accumulated after decay of ^{87}Rb is fixed in the structure of clay minerals together with Sr captured in the course of crystallization. In addition, Sr is a component of authigenic carbonates and phosphates, or it can be adsorbed at the surface of clay particles. In the last case, this element is concentrated either between particles, or in marginal interlayer sites. Leaching the fine subfractions in chemical reagents, we can separate those constituents of the complex Rb–Sr isotopic system, which characterize different minerals or occupy different sites in their structure.

Central interlayer sites in the illite structure are occupied by K^+ and Rb^+ ions. Transition to the peripheral interlayer sites, which are loosed by Mg^{2+} and Sr^{2+} ions partially hydrated and inappropriate to these sites, appears to be gradual. It is likely that NH_4OAc leaches those easily exchangeable ions situated on the stretched "frayed" edges, which got into this place from diagenetic interstitial fluids and also from later solutions that circulated in the exogenesis zone. The cation exchange is less effective in central spheres of clay particles, where many crystal layers turn out to be blockaded or collapsed under influence of NH_4^+ ions. Thus, the ion-exchange reactions with fine particles having the higher surface-to-volume ratios are most effective. Previous investigations showed that leaching does not lead to the differential extraction of radiogenic ^{87}Sr from close-packed sites of mineral structures (Clauer, 1979; Gorokhov *et al.*, 1989, 1994; Clauer *et al.*, 1993). At the same time, it removes Rb and Sr from metathetical interlayer sites accessible for the reagent and from soluble accessory minerals.

Hence, analyzing the isotopic composition of metathetical Sr, we obtain characteristics of fluid that was in contact with clay mineral at some or other stage of its being or transformation. The removal of mobile Sr from clay and accessory minerals increases the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios in residues. The $^{87}Sr/^{86}Sr$ ratio in leachates is always relatively lower. Mass balance in exchange reactions presumes that data points characterizing leachate, residue, and untreated sample should plot along a strait line in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ diagram regardless of real or misleading geochronological sense of the line slope. It is another case, when solid and interstitial liquid phases of the given sedimentary rock were some time in isotopic equilibrium, and the clay fraction of the rock is free of inherited ^{87}Sr and does not represent a mixture of non-cogenetic components. In this case, the line slope corresponds to the time, when the equilibrium was set in, and the intersept, i.e., the intersection point of that strait line ("inner isochron") and ordinate, defines quite strictly the $^{87}Sr/^{86}Sr$ ratio in the interstitial fluid.

All the separated SFs were leached in 1N solution of ammonium acetate (NH_4OAc) under the room temperature and by simultaneous ultrasonic machining during 15 minutes. Advantages of NH_4OAc solution, as compared to other leaching reagents, consist not only in self-buffering by neutral pH, but also in the acetate ion ability to form complex compounds with alkali-earth elements that accelerate the exchange reaction (Morton, 1985). In addition, NH_4OAc is able to dissolve some $CaCO_3$ (Wada and Furumura, 1994) thus decreasing the common Sr content in the SFs. The leached SFs ranged by weight from 60 to 100 mg depending on the material availability. Residues separated from leachates

Table 1. Mineral characteristics of clay subfractions

Particle sizes, μm	Illite polytype	CIS Δ°2θ	I_{002}/I_{001}	Admixture
Sample AN-33				
2–5	n.d.	1.47	0.12	Q, Fsp
0.6–2	n.d.	1.47	0.27	Q, Fsp (tr.)
0.3–0.6	1 Md	1.51	0.67	–
0.2–0.3	1 Md	1.51	1.16	–
0.1–0.2	1 Md	1.51	1.23	–
<0.1	1 Md	1.77	1.27	–
Sample AN-42				
1–2	n.d.	1.23	0.49	Q, Fsp (tr.)
0.6–1	n.d.	1.39	0.64	Q, Fsp (tr.)
0.3–0.6	1 M–1 Md	1.57	0.72	Q, Fsp (tr.)
0.2–0.3	1 Md	1.77	1.51	–
0.1–0.2	1 Md	1.72	1.47	–
<0.1	1 Md	1.86	1.53	–

Note: n.d. denotes not determined.

by centrifuging were washed twice in the bidistilled water, and the obtained portions of salt solution were added to leachates. The Rb–Sr isotopic parameters were studied in all leachates, residues, and untreated SFs.

Rb–Sr analysis. The isotopic dilution method and mixed $^{87}Rb/^{84}Sr$ spike were used to determine the $^{87}Rb/^{86}Sr$ ratios. In most experimental runs, the $^{87}Sr/^{86}Sr$ were measured using the spike as well. After the sample dissolution in the mixture of distilled concentrated HF and H_2SO_4, Rb and Sr were extracted using the ion-exchange resin Dowex AG50W × 8 (200–400 mesh) and subsequent elution with 2.5 N HCl. The Sr isotopic analyses were performed in static mode using the multi-collector mass spectrometer Finnigan MAT 261 with the Re-filament ion source and simultaneous registration of ion currents of all isotopes. During the period of experimental runs, the laboratory average of 0.7105 ± 0.00001 ($n = 9$) was determined for the NBS SRM 987 standard, and the value of 0.70804 ± 0.00002 ($n = 11$) was obtained for the Eimer and Amend standard. The indicated uncertainty corresponds to $2\sigma_{average}$. The $^{87}Rb/^{84}Rb$ ratio was determined using the single-collector mass spectrometer MI 1320 with three-Re-filament ion source (radius 20 cm, deflection angle 90°). Total processing blanks for Rb and Sr varied, but never exceeded 2 and 10 ng, respectively. In the course of measurements, average concentrations of Rb and Sr in the feldspar standard NBS 70a were equal to 522 and 65.5 ppm, respectively; the relevant ratio $^{87}Sr/^{86}Sr = 1.20025$. The analytical uncertainty is estimated to be ±1% for $^{87}Rb/^{86}Sr$ ratios and ±0.1% for $^{87}Sr/^{86}Sr$ ratios.

The Rb and Sr concentrations are evaluated relative to the SF mass before leaching so that $Rb_{(l)} + Rb_{(r)} = Rb_{(ut)}$ and $Sr_{(l)} + Sr_{(r)} = Sr_{(ut)}$, where subscripts denote leachate, residue, and untreated SF, respectively. As a rule, the corresponding mass balance was much better than ±4.0% evidencing correctness of the leaching and analytical procedures.

Parameters of "inner isochrons" defined by data points of leachates, residues, and untreated parental SFs were calculated using method by McIntyre *et al.* (1966), and the statistic uncertainty is assessed according to Williamson (1968). The decay constant $\lambda^{87}Rb = 1.42 \times 10^{-11}$ year^{-1} was used to calculate the isotopic age. All uncertainties in the text and graphs are quoted at the 2σ level.

RESULTS

Mineralogy. Mineral characteristics of clay SFs from the Yusmastakh shales are summarized in Table 1. Predominant in both studied samples are clay particle >0.3 μm in size. Photographs obtained with the help of scanning and transmission electron microscopy (Fig. 2) show that all SFs separated from Sample AN-33 are chiefly composed of pseudohexagonal hypidiomorphic crystals characteristic of authigenic dioctahedral minerals of mica group. According to results of XRD analysis, the SFs of studied shales are actually represented by dioctahedral mica-type mineral rich in K and Al that has some expandable layers. In terms of Srodon and Eberl (1984), the substance can be defined as "illite material" and simply referred to illite in subsequent consideration. In SFs >0.3 μm of both samples and in SF 0.3–0.6 μm of Sample AN-33, illite invariably is represented by the 1Md polytype, whereas the last SF of Sample AN-42 also includes the polytype 1M–1Md. In addition to illite, the relatively coarse SFs (>0.3 μm) include an insignificant admixture of clastic feldspar and quartz, presence of which is especially notable in the SF 2–5 μm of Sample AN-33. Two other mineralogical peculiarities of illite SFs are especially important for understanding of post-sedimentation history of the studied shales.

(1) The CIS values of illite in all SFs are greater than 0.42°, and they vary within the parametric range characterizing the diagenesis zone considerably remote from the anchimetamorphism zone (Fig. 3). As the clay particle decrease in size, the CIS values increase that is most evident in the SF series of Sample AN-42 from the base of the upper Yusmastakh Subformation. The illite crystallinity is proportional to the thickness of the X-ray coherent dispersal zone in its crystal structure (Drits *et al.*, 1997). This parameter is controlled chiefly by temperature, though the porosity and permeability of sediments, as well as composition of diagenetic and later fluids, may also control it (Kisch, 1983). Illites of the diagenesis zone, like the studied ones, reveal a variable, though rather high amount of displacement defects, their packages are rather thin (<100 Å in aver-

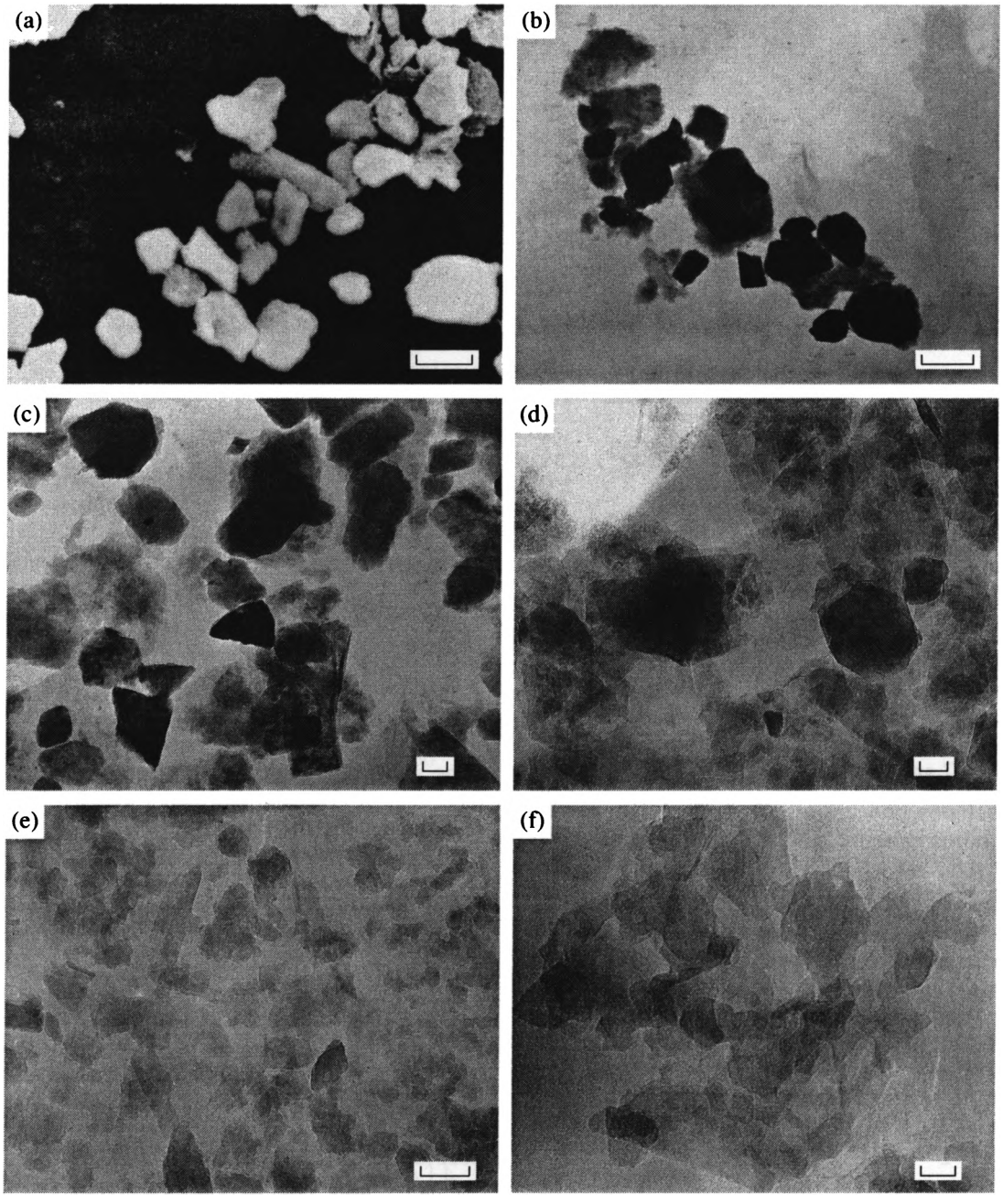

Fig. 2. Microphotographs of clay particles in subfractions of Sample AN-33 under scanning (a) and transmission (b–f) electron microscopes. SFs: (a, b) 0.6–2 μm, scale bar 1.0 μm; (c) 0.3–0.6 μm, scale bar 0.2 μm; (d) 0.2–0.3 μm, scale bar 0.1 μm; (e) 0.1–0.2 μm, scale bar 0.2 μm; (f) <0.1 μm, scale bar 0.05 μm.

age) and have a considerable proportion of expandable layers (Kralik and Schramm, 1994; Dong *et al.*, 1995). Differences in crystallinity indices of illites from fine and coarser SFs may point to their origin at different stages of lithogenesis.

(2) As the particle size decreases, the ratio between 5 Å- and 10 Å-reflections (I_{002}/I_{001}) rapidly grows in both samples (Fig. 4). This ratio is considered as indicating proportion between Al, on the one hand, and Fe and Mg, on the other, in the octahedral layer of illite (Esquevin, 1969; Srodon and Eberi, 1984). Hence, the obtained data may indicate that the fine SFs contain more Al than the coarser ones, and this accords with the above assumption that constituent minerals of these SFs are non-cogenetic.

Rb–Sr data. The Rb–Sr data obtained for each illite SF of shales from the Yusmastakh Formation are used to plot the corresponding "inner isochrons" (Figs. 5 and 6)

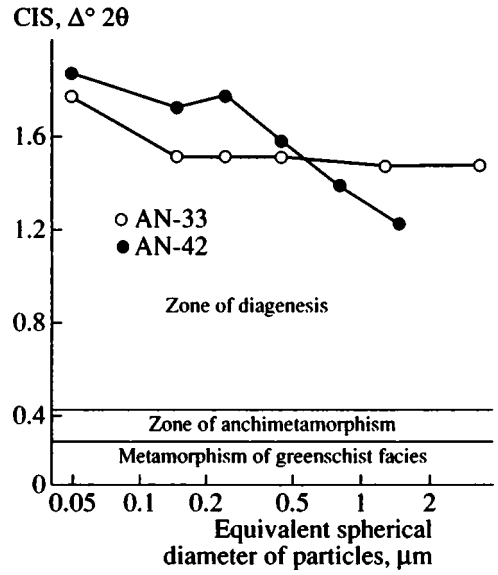

Fig. 3. Variations of crystallinity index standard (CIS) versus size of illite particles.

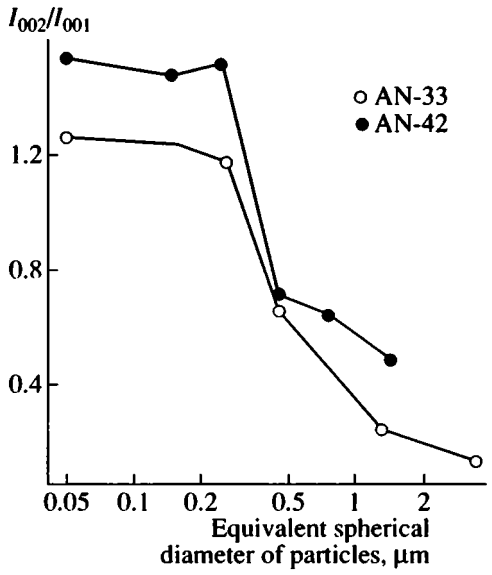

Fig. 4. Variations of I_{002}/I_{001} ratios versus size of illite particles.

and to calculate the apparent ages and initial $^{87}Sr/^{86}Sr$ ratios. As the size range of SFs from both studied samples decreases, we observe the following variation trends in Rb–Sr isotopic characteristic of illites (Table 2, Figs. 7 and 8):

(1) In leachates, concentrations of Rb and Sr, as well as $^{87}Sr/^{86}Sr$ ratios increase. The smooth variation of the latter from 0.81988 to 0.93475, as the particle size decreases, is slightly violated in the finest SFs only.

(2) Residues show approximately two-fold decrease in the Sr concentrations. In both samples, deviations from this trend are characteristic of their coarse SFs only that is understandable in view of feldspar and quartz admixture in these SFs (Table 1). In contrast, the Rb concentrations considerably grow by transition from coarse- to medium-sized SFs. Away from one or two finest SFs, the $^{87}Rb/^{86}Sr$ ratios show trend to grow steadily, as the grain size decreases.

(3) The apparent Rb–Sr age decreases from 1272–1284 Ma in coarse SFs to 1004–1048 Ma in fine SFs (Figs. 5–7). Initial $^{87}Sr/^{86}Sr$ ratios vary in this case from 0.7445 to 0.8311 (Figs. 5, 6, and 8). Accordingly, the last parameter of all SFs exceeds that of the Middle–Late Riphean seawater, where it changes from 0.7049 to 0.7062 (Gorokhov *et al.*, 1995, 1996).

In addition to these common trends, the Rb–Sr systematics for samples AN-33 (lower subformation) and AN-42 (upper subformation) turn out to be different in some details:

(1) In the SF series of Sample AN-33, the Rb concentrations invariably grow from the coarsest to penultimate SF (0.1–0.2 μm). In the other series of Sample AN-42, their initial growth transforms into the slow downward trend beginning from the SF with the particle size range of 0.6–1 μm.

(2) As the particle size decreases in SFs of Sample AN-33, the initial $^{87}Sr/^{86}Sr$ ratio increases smoothly up to the value characterizing the SF 0.1–0.2 μm, but this parameter slightly drops in the finest SF (<0.1 μm). If we consider the data set for Sample AN-42, the same ratio first increases sharply, when the grain-size range declines from 1–2 to 0.6–1 μm, afterward it remains approximately constant, and then, in two finest SFs, we observe its considerable drop of comparable magnitude (Fig. 8).

(3) In the case of Sample AN-33, the apparent age of SFs gradually decreases from 1272 to 1004 Ma, as illite particles diminish in size from 0.6–0.2 to <0.1 μm. For SFs of Sample AN-42, it lowers stepwise from 1284 Ma in SF 1–2 μm to 1028 Ma in SF 0.6–1 μm and remains afterward at the approximately constant level (1048–1093 Ma) in finer SFs (Fig. 7).

Data points characterizing leachates (Fig. 9) and residues after leaching (Fig. 10) plot in most cases along linear trends in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ diagram. Significant deviations from these trends are typical of data points related to the finest illite particles, namely to SFs <0.1 and 0.1–0.2 μm of Sample AN-33 and to SF <0.1 μm of Sample AN-42. These and other established peculiarities are discussed below, after consideration of some general problems of the Rb–Sr systematics.

DISCUSSION

In order to interpret correctly the dating results for the Yusmastakh shales, we should consider first the Rb–Sr systematics of two-component mixing and three other problems concerning the following topics: (1) geochemi-

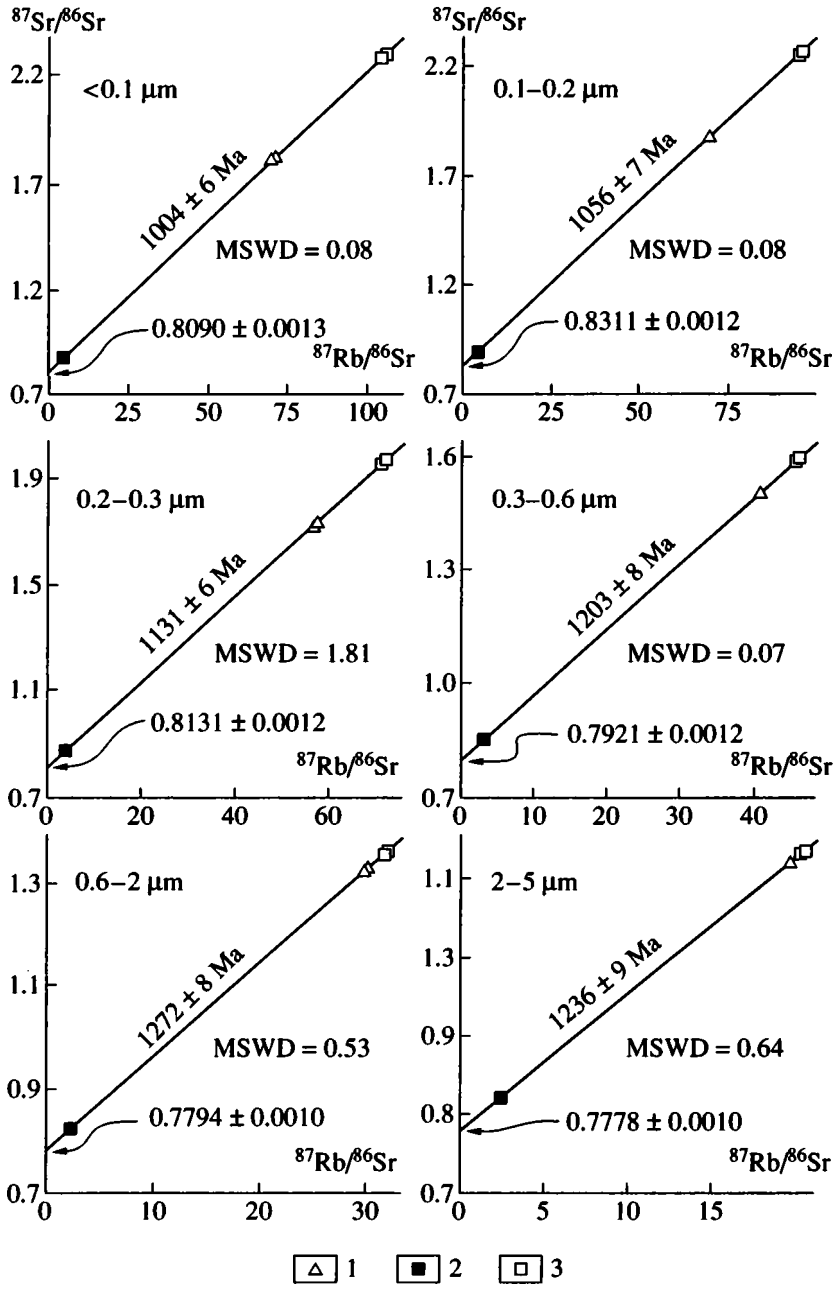

Fig. 5. Inner Rb–Sr isochrons for illite subfractions of Sample AN-33: (1) untreated material; (2) acetate leachates; (3) residues after leaching.

cal significance of $^{87}Sr/^{86}Sr$ ratios measured in acetate leachates of fine illite SFs; (2) geochemical meaning of initial $^{87}Sr/^{86}Sr$ ratios inferred on the basis of "inner Rb–Sr isochrons;" and (3) possibility of using these isochrons for dating the real events in the geological history of sedimentary rocks.

Rb–Sr systematics of two-component mixing. Judging from gradual changes of mineralogical and chemical characteristics of the studied clay SFs decreasing in size range, we may suspect that each SF represent a mixture of two end members different in age and composition. This assumption finds a support in the model considerations presented below.

Let us consider a mixture of components 1 and 2, quotas of which are Θ and $(1 - \Theta)$. Suppose the atom concentrations of three isotopes equal to $^{87}Rb_1$, $^{87}Sr_1$, $^{86}Sr_1$ and $^{87}Rb_2$, $^{87}Sr_2$, $^{86}Sr_2$ in the end members, and to $^{87}Rb_m$, $^{87}Sr_m$, $^{86}Sr_m$ in the mixture. What we have to figure out are the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios in the mixture and its end members, as well as positions of

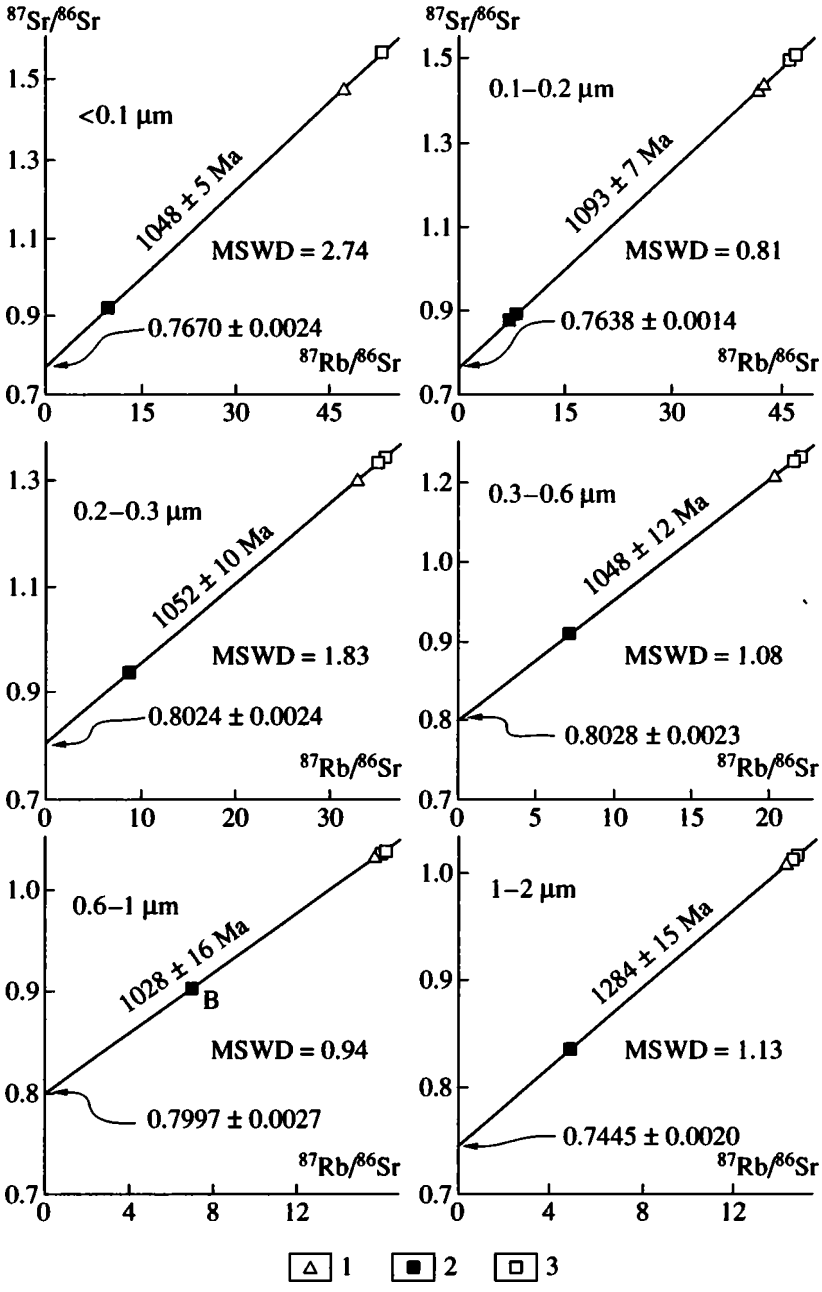

Fig. 6. Inner Rb–Sr isochrons for illite subfractions of Sample AN-42: (1) untreated material; (2) acetate leachates; (3) residues after leaching.

respective data point in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ diagram. Let us calculate ratios $(^{87}Rb/^{86}Sr)_m$ and $(^{87}Sr/^{86}Sr)_m$ in the mixture. According to the mass balance, we can state that the ^{87}Rb concentration in the mixture is

$$^{87}Rb_m = {}^{87}Rb_1\Theta + {}^{87}Rb_2(1-\Theta) \quad (1a)$$

$$^{87}Sr_m = {}^{87}Sr_1\Theta + {}^{87}Sr_2(1-\Theta) \quad (1b)$$

and

$$^{86}Sr_m = {}^{86}Sr_1\Theta + {}^{86}Sr_2(1-\Theta). \quad (1c)$$

Consequently, the isotopic ratios can be expressed as

$$\left(\frac{^{87}Rb}{^{86}Sr}\right)_m = \frac{^{87}Rb_1\Theta + {}^{87}Rb_2(1-\Theta)}{^{86}Sr_1\Theta + {}^{86}Sr_2(1-\Theta)} \quad (2)$$

and

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_m = \frac{^{87}Sr_1\Theta + {}^{87}Sr_2(1-\Theta)}{^{86}Sr_1\Theta + {}^{86}Sr_2(1-\Theta)}$$

Table 2. Data of Rb–Sr analysis for clay subfractions

Particle sizes, μm	Analyzed material*	Rb, ppm**	Sr, ppm**	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
		Sample AN-33			
2–5	UT	141	21.6	19.62	1.12548
	L	0.555	0.683	2.378	0.81988
	R***	140	20.8	20.27	1.13784
		140	20.8	20.26	1.13480
0.6–2	UT	161	16.5	29.94	1.32788
		162	16.6	30.02	1.32689
	L	0.971	1.20	2.366	0.82254
	R***	161	15.6	31.79	1.35676
		160	15.5	31.88	1.35905
0.3–0.6	UT	272	20.9	40.61	1.49311
	L	3.03	2.63	3.387	0.85048
	R***	268	18.4	45.78	1.58034
		267	18.3	46.03	1.58499
0.2–0.3	UT	358	20.2	56.36	1.72809
		360	20.1	56.98	1.74088
	L	6.14	4.51	4.007	0.87798
	R***	348	15.7	72.22	1.98362
		351	15.8	72.19	1.97026
0.1–0.2	UT	373	17.4	69.28	1.87867
	L	6.81	4.91	4.088	0.89287
	R***	365	12.9	94.42	2.25479
		365	12.7	95.90	2.28012
<0.1	UT	361	16.4	70.65	1.82264
		358	16.3	70.29	1.81774
	L	9.47	5.39	5.174	0.88329
	R***	351	11.1	106.1	2.32880
		350	11.1	105.6	2.32713
		Sample AN-42			
1–2	UT	193	39.4	14.60	1.01382
	L	1.71	1.02	4.913	0.83486
	R***	192	38.8	14.71	1.01326
		187	37.8	14.78	1.01730
0.6–1	UT	272	50.6	16.06	1.03704
	L	4.32	1.81	7.061	0.90353
	R***	262	48.5	16.16	1.03597
		259	47.9	16.13	1.03722
0.3–0.6	UT	332	49.2	20.34	1.10877
	L	6.80	2.80	7.172	0.91028
	R***	329	45.4	21.83	1.12797
		327	45.3	21.72	1.12933
0.2–0.3	UT	328	30.7	32.66	1.29757
	L	10.6	3.58	8.790	0.93475
	R***	320	27.6	35.63	1.33511
		318	27.6	35.32	1.33435
0.1–0.2	UT	323	23.8	42.09	1.42204
	L***	322	23.5	42.47	1.43226
	R***	10.6	3.95	7.891	0.88871
		8.14	3.30	7.265	0.87748
	O***	311	20.7	46.94	1.49688
		313	20.5	47.70	1.51022
<0.1	UT	311	20.6	47.01	1.47852
	L	13.6	3.98	10.10	0.92132
	R***	299	17.0	55.13	1.58715
		297	17.5	53.41	1.56653

* (UT) untreated clay SF, (L) leachate, (R) residue after leaching; ** Rb and Sr concentrations in leachates and residues are recalculated for 1 g of untreated SFs; ***data in this and next row are the results of duplicate leaching.

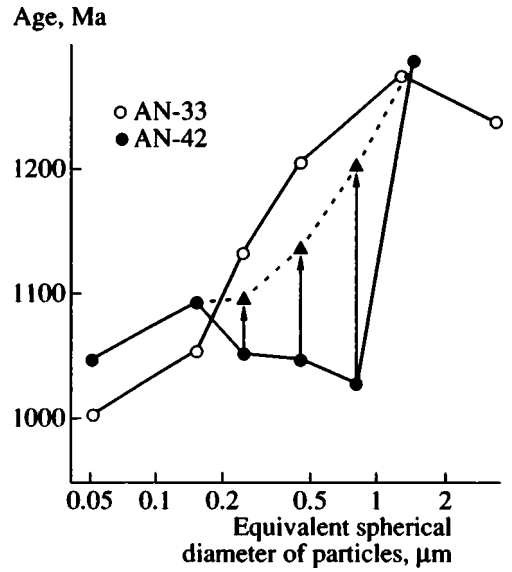

Fig. 7. Diagram of apparent Rb–Sr age versus particle size of analyzed illite subfractions. Triangles denote the apparent ages that are considered as original for corresponding subfractions of Sample AN-42 in accord with results of mathematically simulated isotopic exchange of mobile Sr with hypothetical solution having the relatively high $^{87}Sr/^{86}Sr$ ratio (see text for additional explanations).

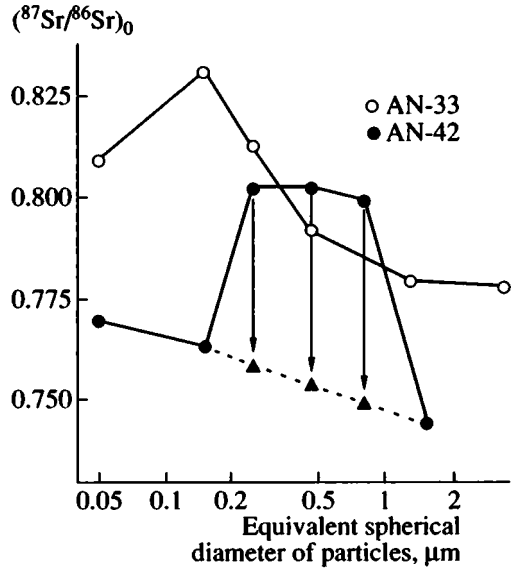

Fig. 8. Diagram of initial $^{87}Sr/^{86}Sr$ ratio versus particle size of analyzed illite subfractions. Triangles denote the ratios that are calculated for corresponding subfractions of Sample AN-42 in accord with results of mathematically simulated isotopic exchange of mobile Sr with hypothetical solution having the relatively high $^{87}Sr/^{86}Sr$ ratio (see text for additional explanations).

After simple transformations, we obtain

$$\left(\frac{^{87}Rb}{^{86}Sr}\right)_m = \frac{(^{87}Rb/^{86}Sr)_1\Theta + \gamma(^{87}Rb/^{86}Sr)_2(1-\Theta)}{\Theta + \gamma(1-\Theta)} \quad (3)$$

and

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_m = \frac{(^{87}Sr/^{86}Sr)_1\Theta + \gamma(^{87}Sr/^{86}Sr)_2(1-\Theta)}{\Theta + \gamma(1-\Theta)},$$

where $\gamma = {}^{86}Sr_2/{}^{86}Sr_1$ is the ratio of ^{86}Sr concentrations in the end members 2 and 1.

The system of equations (3) leads to the following expression

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_m = \frac{(^{87}Rb/^{86}Sr)_2(^{87}Sr/^{86}Sr)_1 - (^{87}Rb/^{86}Sr)_1(^{87}Sr/^{86}Sr)_2}{(^{87}Rb/^{86}Sr)_2 - (^{87}Rb/^{86}Sr)_1} + \frac{(^{87}Sr/^{86}Sr)_2 - (^{87}Sr/^{86}Sr)_1}{(^{87}Rb/^{86}Sr)_2 - (^{87}Rb/^{86}Sr)_1}\left(\frac{^{87}Rb}{^{86}Sr}\right)_m \quad (4)$$

which represents the straight-line equation of form $Y = a + bX$ in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ coordinate system. That is why data points characterizing various proportions of end members 1 and 2 must plot in this coordinate system along the straight line connecting the end-member points. This is exactly the case that one can see in diagrams characterizing correlation between isotopic ratios in leachates (Fig. 9) and residues (Fig. 10) of size-variable SFs from the Yusmastakh shales.

At the same time, linear trends in the diagrams under consideration could be considered alternatively as isochrons, if we assume that the size-variable SFs consist of a single illite generation. In this case, the linear arrangement of data points in Figs. 9 and 10 would define the well-known expression

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t} - 1), \quad (5)$$

that again represents the straight-line equation of form $Y = a + bX$ in the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ diagram. The slope of this line is proportional to the age t of illite formation (recrystallization), and the intersection point of the line and ordinate corresponds to the uniform initial ratio $(^{87}Sr/^{86}Sr)_0$ in mineral particles regardless of their size.

To settle the dilemma (mixing line or isochron) as applied to shales of the Yusmastakh Formation, let us consider chemical peculiarities of SFs residues after leaching (Table 2). Linear trends shown in Fig. 10 cannot be interpreted in terms of the isochron model, since the chemical analysis demonstrated considerable variations of Al/(Fe + Mg) ratio in size-variable SFs and the Rb/Sr ratio growth, when the clay particles decrease in size. Both trends would be improbable, if the SFs consisted of a single illite generation. In the last case, larger illite grains originated by dissolution and recrystallization of smaller particles of this mineral (Ostwald ripen-

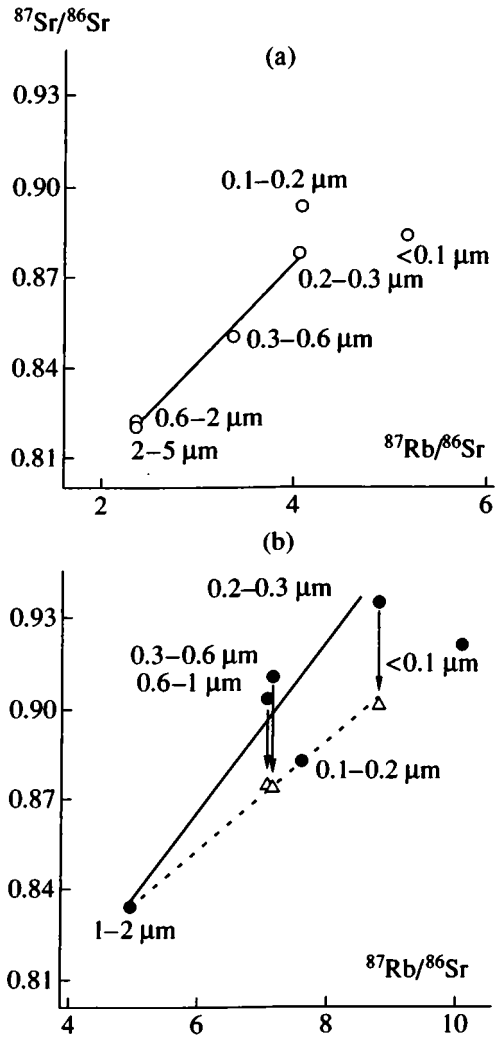

Fig. 9. Rb–Sr mixing diagram for acetate leachates of illite subfractions from samples AN-33 (a) and AN-42 (b). Triangles denote data points that are considered as original for corresponding subfractions of Sample AN-42 in accord with results of mathematically simulated isotopic exchange of mobile Sr with hypothetical solution having the relatively high $^{87}Sr/^{86}Sr$ ratio (see text for additional explanations).

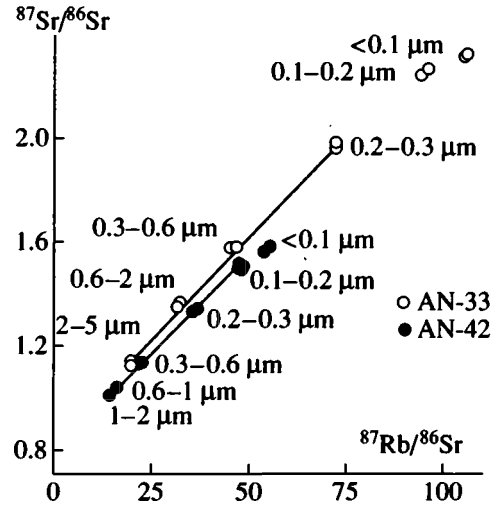

Fig. 10. Rb–Sr mixing diagram for residues after leaching of illite subfractions from samples AN-33 (open circles) and AN-42 (solid circles).

ing) should be characterized by lower Sr concentrations and higher Rb/Sr ratios (Eberl *et al.*, 1990; Kralik and Schramm, 1994) that is not the case under consideration. Moreover, the apparent Rb–Sr ages of leachates and residues, if we calculate them on the basis of regression slopes in Figs. 9 and 10, considerably differ from each other, and the age range of 1950–2300 Ma calculated for leachates does not make a sense, as it is much greater than the stratigraphically defined age of samples.

Thus, the linear regressions plotted in Figs, 9 and 10 cannot be considered as isochrons. All the data obtained suggest that most of SFs from both shale samples represent the two-component mixtures of authigenic illites different in composition and age, so that coarser and finer SFs are enriched in older and younger components, respectively.

Geochemical sense of $^{87}SR/^{86}Sr$ ratio in acetate leachates. As for the identity of Sr extractable from clay minerals in the course of laboratory leaching, it is interpreted controversially. According to one viewpoint (Clauer, 1976, 1979; Clauer *et al.*, 1984, 1990; Gorokhov *et al.*, 1994), this Sr characterizes fluid that surrounded clay minerals during their formation, and the leaching procedure offers therefore an opportunity to determine the Sr isotope composition in diagenesis or catagenesis zones. In the alternative opinion (Ohr *et al.*, 1991; Awwiller, 1994; Vinogradov, 1997), acetate or acid leachates characterize the Sr isotope composition in the latest interstitial solution that was in contact with clay particles and might be out of relation to their formation medium. Data shown in Figs. 9 and 10 shed some light on the issue as applied to the studied shales.

In both indicated diagrams, most significant deviations from the mixing lines are characteristic of data points corresponding to the finest SFs. These are SFs <0.1 μm of both rock samples and SF 0.1–0.2 μm of Sample AN-33 in the diagram for residues after leaching (Fig. 10), and all SFs of the same size ranges in the diagram for leachates (Fig. 9). Accordingly, neither residues nor leachates of these SFs can be considered as characterizing end members of those two-component mixtures, which define composition of coarser SFs. At the same time, the aforementioned peculiarity of diagrams helps to understand the identity of solutions that introduced the mobile Sr into shales of the Yusmastakh Formation. The most simple and, apparently, most realistic assumption is that two illite generations ("younger" and "older"), i.e., two end members defin-

ing mixing lines in Fig. 10, originated in different media, which were equivalent, in terms of Rb–Sr systematics, to the end members of mixtures extracted by leaching (Fig. 9). The contrary postulation that the Sr isotope composition in leachates corresponds to that in the late interstitial solution irrelevant to the illite genesis confronts the available data. If this would be the case then, provided that the two-component mixing model of mobile Sr in the studied shales is out of doubts, the most fine-grained SFs (<0.1 μm) with their highest adsorption ability should be corresponding in the Rb–Sr diagram to the "younger" end members of the mixture. In fact, we have another situation, and these members are represented in Fig. 9 by coarser SFs. On the contrary, data points of the finest SFs deviate from mixing lines not only in this, but also in the other diagram characterizing the residues after leaching that is even more important.

Thus, we can conclude that recent or slightly older interstitial solutions cannot be accepted for the general source of mobile Sr leachable from SFs of the Yusmastakh shales. Nevertheless, the influence of these solutions on isotopic composition of mobile Sr may result in a certain displacement of leachate data points from the mixing lines that may change, in turn, geochronological parameters of the isochron.

The above statement can be illustrated with the help of Sample AN-42, as its SFs do not reveal a smooth succession of apparent ages and initial $^{87}Sr/^{86}Sr$ ratios in Figs. 7 and 8, on the one hand, but show a considerable dispersion of data points characterizing leachates in Fig. 9b, on the other. If we suppose that this dispersion is a result of isotopic exchange between a part of the mobile Sr of some SFs and more radiogenic Sr introduced by a hypothetical fluid, then the initial isotopic composition of the former can be calculated by means of mathematical simulation. The substitution of initial for present-day $^{87}Sr/^{86}Sr$ ratios in some SFs of Sample AN-42 automatically changes ordinates of data point characterizing leachates in Fig. 6, and this naturally modifies the apparent ages and initial $^{87}Sr/^{86}Sr$ ratios for corresponding SFs in Figs. 6, 7, and 8. Accordingly, our task was to simulate such a regression line for data points of leachates in Fig. 9b that would lead to the gradual changes of apparent ages and initial $^{87}Sr/^{86}Sr$ ratios of size-variable SFs in Figs. 7 and 8, which would resemble variation trends of the same parameters characterizing Sample AN-33.

The results of simulation are shown in Figs. 7, 8, and 9b, where the calculated initial (prior to the isotope exchange of mobile Sr with a hypothetical fluid) characteristics of some intermediate SFs of Sample AN-42 are indicated by triangles and related arrows pointing to data points that depict the real experimental results. Dashed lines in these graphs connect original positions of corresponding points. As one can see, the simulation results convincingly show that isotopic parameters of shale samples from lower and upper Yusmastakh subformations differ because the mobile Sr of some SFs of Sample AN-42 could be in isotopic exchange with fluid that had a rather high $^{87}Sr/^{86}Sr$ ratio. It is important therefore that the dolomite–siliciclastic horizon, from which Sample AN-42 is collected, is rather permeable, discharging a small amount of ground water.

The mathematical simulation allowed us to obtain coordinated mixing lines for the acetate leachates and residues of SFs from Sample AN-42 (Figs. 9b and 10). This important result suggests that both the immobile and mobile Sr in this clayey material characterize mixtures of end members corresponding to SFs with size ranges of 1–2 and 0.1–0.2 μm. At the same time, data points of SF <0.1 μm deviate from mixing lines in both indicated diagrams. Consequently, we may assume that the Sr isotope exchange in shales of the upper Yusmastakh Subformation took place *after* the origin of second illite generation and its mixing with older illite of the first generation, but *prior* to the illite crystallization in SF <0.1 μm. We cannot establish, however, the identity of fluid that disturbed the Rb–Sr isotopic systems in SFs 0.6–1, 0.3–0.6, and 0.2–0.3 μm of Sample AN-42. It also remains unclear why the data point of SF 0.1–0.2 μm is displaced along the mixing line from the extreme into the intermediate position.

Nevertheless, we suppose, with a certain reservation, that fluid responsible for crystallization of clay particles represented simultaneously the main source of mobile Sr leachable in laboratory experiments. Hence, this procedure is very useful, offering the opportunity to obtain the important and quite authentic information about conditions of mineral formation in shales, e.g., about the composition of diagenetic or catagenetic fluids.

The high initial $^{87}Sr/^{86}Sr$ ratios in illites corresponding to end members of the mineral mixture may be: (1) either the result of authigenesis of clay minerals soon after sedimentation within a medium that was out of equilibrium with the seawater Sr, or (2) the consequence of their much later crystallization in the interstitial solutions also different in composition from the sedimentation medium.

In the first case, we should presume that the closed system, where migration of elements during minerals crystallization was insignificant, appeared at the early stage of sediment burial. If this is the case, the initial $^{87}Sr/^{86}Sr$ ratio in clayey material must be proportional to the amount of those authigenic minerals, which formed after the system isolation from seawater. Indeed, the illite formation in a closed system lacking the renewal of interstitial fluids should be associated with congruent dissolution of detrital particles that yield necessary cations. This dissolution adds to the interstitial medium the radiogenic ^{87}Sr, and such a situation may explain the higher initial $^{87}Sr/^{86}Sr$ ratios in authigenic minerals formed in these environments (Clauer *et al.*, 1990; Gorokhov *et al.*, 1994). The proportion of silicate Sr in the interstitial fluid can be as

high as 45% (Awwiller, 1994). The described mechanism was apparently responsible for origin of the first, "older" illite generation in shales of the Yusmastakh Formation.

The second mechanism requires the fluid regime transformation at some later stages of lithogenesis, when sedimentary strata subside deeper or, on the contrary, rise up to the circulation zone of meteoric waters. In this case, clay minerals most likely crystallize or suffer recrystallization in an open system, and intensity of these processes must depend on the rock permeability. We assume that this mechanism resulted in origin of the second, "younger" illite generation in the studied samples.

The fact that data points characterizing leachates and residues of the finest SFs show correlative deviations from mixing lines means, in our opinion, that illite of these SFs originated in a medium with Rb–Sr parameters different from those in solutions, where the earlier generations of this mineral crystallized. Consequently, we may suspect either changes in the fluid composition at the last crystallization stages of the second illite generation, or a separate third and last episode of illite formation.

Interpretation of Rb–Sr ages calculated using the "inner isochrons." If the above conclusion that the immobile and mobile Sr in clay SFs are cogenetic is valid, we obtain a possibility to date the *end members* of mixtures using the "inner isochrons," which are based on data point triplets characterizing leachate, residue, and untreated material of a given SF. In the case of authigenic SFs corresponding to end members of a mixture, these isochrons date the real, chronologically discrete events. This could be, for instance, either the transformation of original smectite or mixed-layer illite–smectite into the 1Md illite polytype under influence of growing temperature and/or K concentration in the interstitial solution, or the recrystallization of clay minerals in response to influx of a new interstitial fluid. Transformations of this kind usually increase the K and Rb concentration in the mineral that results in formation of closed non-expandable interlayers, and, simultaneously, they lead to the isotopic equilibrium between the interstitial fluid and Sr occupying the interlayer sites. The inner isochron ages have geochronological implications only then, when the last condition is fulfilled.

The apparent Rb–Sr ages calculated for both studied samples on the basis of inner isochrons vary from 1284 ± 16 to 1004 ± 6 Ma gradually decreasing, as the size range of SFs diminishes. We should remind here that many of the studied SFs represent the two-component mixtures of non-cogenetic illites. Accordingly, all ages of SFs, which do not correspond to end members of mixtures, have no geochronological meaning.

As is shown above (Fig. 10), the "older" end members of mixtures are represented in both rock samples by coarse SFs containing the first illite generation (SF 0.6–2 μm in Sample AN-33 and SF 1–2 μm in Sample AN-42). The corresponding ages of their inner isochrons (Figs. 5 and 6) are 1272 and 1284 Ma. Both values are concordant to each other and also to the age range of the Yusmastakh Formation inferable from the C-isotope chemostratigraphy and paleontological data, as well as from Rb–Sr and K–Ar dates obtained for sedimentary geochronometers from the underlying Riphean horizons of the Kotuikan section (see above). A somewhat younger date of 1236 ± 9 Ma is calculated for SF 2–5 μm of Sample AN-33, and this may be caused by the feldspar admixture in that SF. The assumption seems to be paradoxical, because the addition of clastic feldspar that is undoubtedly older than authigenic clay minerals should decrease, but not increase the apparent age of this SF. The regression line for the SF in question (Fig. 5) is, however, not an isochron proper, because the residue after leaching includes in this case a considerable proportion of feldspar genetically incompatible with illite, and, as is known, it is much easier to leach Sr from phyllosilicates, than from tectosilicates (e.g., see Gorokhov *et al.*, 1984, 1995). Consequently, the $^{87}Sr/^{86}Sr$ ratio in the leachate from that SF characterizes the crystallization medium of the first illite generation, being much higher than the initial $^{87}Sr/^{86}Sr$ ratios presumably ranging from 0.705 to 0.710 and characterizing feldspar-bearing rocks in the provenance of sedimentary material under consideration. Thus, the respective regression line in Fig. 5 corresponds to the situation, when the younger clay minerals are mixed with older material, the initial $^{87}Sr/^{86}Sr$ ratio of which is lower (its Rb/Sr ratio seems to be not very high as well). When incorrectly applying the isochron model to this mixture, we obtain the initial $^{87}Sr/^{86}Sr$ ratio 0.7778 that is too high, and the calculated apparent age turns out to be lower than the real age of the clay minerals and lacks geochronological sense.

The second illite generation is most concentrated in "younger" end members of mixtures represented by SF 0.2–0.3 μm in Sample AN-33 and by SF 0.1–0.2 μm in Sample AN-42 (Fig. 9 and 10). Age values of 1093 and 1131 Ma corresponding to these SFs (Figs. 5 and 6) can be considered as defining the maximum age of the process that caused crystallization of the second illite generation in shales of the Yusmastakh Formation. Finally, for the latest illite generation of finest SFs that cannot be included into the systematics of mixing, we calculated the Rb–Sr ages of 1004 ± 6 and 1048 ±5 Ma (Figs. 5 and 6) for the samples from lower and upper Yusmastakh subformations, respectively.

Interpreting geological significance of the results obtained, we should consider the following alternative: (1) accumulation periods of lower and upper Yusmastakh subformations were separated by a considerable time gap; the burial diagenesis of their sediments took place 1270–1280 and 1090–1130 Ma ago, respectively; and the old illite (1284 ± 15 Ma) in shales of the upper subformation is detrital; (2) sediments of both subformations accumulated during a short period, and the burial diagenesis responsible for origin of the first illite

generation happened 1270–1280 Ma ago, whereas the second illite generation was formed in the course of superimposed event (or events) that affected both subformations 1090–1130 Ma ago. As for the third youngest illite generation, it should bear, in any case, the signatures of latest events in the history of lithogenesis of the studied sediments.

The first version seems to be hardly probable because of two reasons. First, it is difficult to explain, in this case, the synchronous origin of the second illite generation in lower and upper subformations. Second, this version contradicts the results of C-isotope chemostratigraphy, which imply that both units are not younger than 1250 Ma (see above). The second version is more plausible, and we suggest below the following scenario that explains the diversity of Rb–Sr ages established for various SFs from the two shale samples studied. This scenario is based on the following conclusions substantiated above: illite is represented in the studied shales by three authigenic generations originated in media that differed from each other in their Sr isotope composition at least, and crystallization periods of these generations were separated in time.

The Yusmastakh deposits accumulated at the very beginning of the Middle Riphean during a short period of geological time (not more than 10 m.y.), and their burial diagenesis about 1270–1280 Ma ago resulted in origin of the first illite generation (SF 0.6–2 μm in Sample AN-33 and SF 1–2 μm in Sample AN-42). This inference is based on several complementary arguments. Data of paleontology and C-isotope chemostratigraphy show that the accumulation period of the Yusmastakh Formation falls within the time range of 1350–1250 Ma, and isotopic Rb–Sr ages obtained for the first illite generation of both subformations (1284 ± 8 and 1272 ± 8 Ma) are concordant to the K–Ar age (1270 Ma) of globular glauconite from the base of the lower subformation (*Geokhronologiya...*, 1968). The mentioned Rb–Sr data specify the time of the burial diagenesis, and their mutual coincidence suggests that this event affected the Yusmastakh Formation as whole. Concrete data on thermal conditions of this process are unknown, but the color index of organic-walled microfossils from the Ust'-Il'ya and lower Kotuikan deposits occurring 250–350 m below the Yusmastakh Formation indicates that rocks of these units, except for their narrow contact zones with hypabyssal intrusions, were never heated to the temperature above 60–70°C (Gorokhov *et al.*, 1991). The heating degree of Yusmastakh rocks should be lower, rather than higher, and this factor was consequently unable to decrease the isotopic ages of corresponding illites and glauconites.

The "younger" (1090–1130 Ma) end members of the studied two-component mixtures (SF 0.2–0.3 μm in Sample AN-33 and SF 0.1–0.2 μm in Sample AN-42) presumably recorded the event of incipient exhumation of Riphean rocks in the Anabar massif. This event and corresponding changes in composition of interstitial solutions resulted in the authigenic formation of the second illite generation in the Yusmastakh deposits. The indicated Rb–Sr dates are comparable with K–Ar ages of1070–1120 Ma known for glauconites from the upper Yusmastakh Subformation (*Geokhronologiya...*, 1968), and this coincidence can be considered as proving the event reality, though it provides no information with respect to the nature of the latter.

Afterward, the Yusmastakh deposits ascended to the circulation zone of meteoric waters, the influence of which is a leading factor of regressive catagenesis. The Rb–Sr dates obtained for the finest Al-enriched 1Md illites (SFs <0.1 μm in both samples and SF 0.1–0.2 μm in sample AN-33) apparently mark such a catagenetic event that ended 1000–1060 Ma ago. In Figs. 9 and 10, the corresponding data points considerably deviate from general regression lines, thus indicating that crystallization media of the second and last illite generations differed in their Sr isotope composition. The corresponding geological events apparently were separated in time. The suspected further ascent of Yusmastakh deposits can be supported by the fact that the date of 1048 ± 5 Ma obtained for SF <0.1 μm from the upper subformation is older than the date of 1004 ± 6 Ma characterizing the shale sample from the lower, relatively older subformation. This apparent contradiction is easily explainable in terms of the suggested scenario. Indeed, during the ascent of Riphean deposits of the western Anabar massif, the upper Yusmastakh Subformation located at the higher stratigraphic level must get under influence of the changed fluid regime earlier than the lower one. Moreover, the scenario presumes that the upper subformation resided under conditions, which were favorable for the recrystallization of clay minerals and subsequent origin of new illite generation, longer than the lower subformation. These circumstances facilitated the Sr isotope exchange between the relatively coarse SFs of Sample AN-42 and fluid, wherein the $^{87}Sr/^{86}Sr$ ratio was high, and, consequently, the disturbance of isotopic systems of the sample. Another factor that could play some role in this case is the aforementioned better permeability of rocks at the stratigraphic level of this sample.

CONCLUSION

Analyzing the results obtained, we arrive at the following conclusions, significance of which extends far beyond the study region:

(1) The used multidisciplinary approach to age determination of the Yusmastakh Formation appears to be quite effective and applicable for other Precambrian deposits. The available data of paleontology and C-isotope chemostratigraphy show that this formation belongs to the lower Middle Riphean; they also outline its relatively wide time range (~1350–1250 Ma) and constrain geological interpretation of the formerly known (K–Ar dates for globular glauconite) and newly obtained (Rb–Sr dates for size-variable submicron clay

subfractions) data of isotopic geochronology concerning this formation.

(2) It is demonstrated once again that a set of very fine clay subfractions mentioned above and their XRD characteristics enable the Rb–Sr isotopic dating of Precambrian shales. As is established, the laboratory leaching yields data elucidating parameters of the illite crystallization medium. Accordingly, the inner isochrons plotted on the basis of triplets, characterizing the untreated matter, leachates and residues after leaching, can be used for the reliable Rb–Sr dating of end members of illite mixtures. If authigenic illite subfractions correspond to the end members, the isochrons in question date the real events discrete in time. The precision of corresponding age determinations naturally depends on the correct identification of these end members (Rublev, 1998). Dating results for "intermediate" subfractions are lacking geochronological meaning.

(3) It is proved that shales of the Yusmastakh Formation include mixtures of three generations of authigenic illites different in age—the older generation is concentrated in coarser subfraction, and two younger prevail in finer ones. The formation media of these generations differed from each other in the Sr isotope composition.

(4) The Rb–Sr isochron dating that was carried out shows that the Yusmastakh Formation accumulated and underwent the burial diagenesis during a short geological period (apparently, less than 10 m.y.) about 1270–1280 Ma ago. During the subsequent ascent and renewal of interstitial fluids, there were two events 1090–1130 and 1000–1060 Ma ago, when these deposits experienced low-temperature catagenetic alterations that resulted in origin of new generations of authigenic illite.

(5) Results of this study refine the currently accepted time ranges of two well-known stromatolite genera *Gymnosolen* and *Boxonia*. They show that their first endemic representatives *Gymnosolen furcatus* Kom. and *Boxonia lissa* Kom. appeared in the Middle Riphean, but not in younger deposits, as it was accepted before.

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Stages in Development of the Silurian Fauna and Flora in the Type Areas of East Siberia

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Abstract—Three hundred twenty one species of graptolites, chitinozoans, acritarchs, cephalopods, trilobites, brachiopods, scolecodonts, conodonts, bryozoans, ostracodes, gastropods, crinoids, tetracorals, tabulates, heliolitids, stromatoporoids, and tentaculitids were recorded in the Silurian type areas of East Siberia. Three type areas, namely, Moiero, Turukhansk, and Noril'sk, are situated within the belt of shallow shelf facies predominantly bearing benthic species intermediate between the deep-water and shoal biotas. Faunal and floral evolutionary stages were analyzed within local biointervals that correspond to the global biointervals (biochrons). The species of wide and limited stratigraphic ranges and peculiarities of their appearance and disappearance were revealed. The major trend of species evolution in the type Silurian areas of East Siberia is their mass appearance and disappearance at the initial and terminal Silurian time. This was associated with the global Silurian transgression at the beginning of the period and with the global regression at the end. Both events affected most sedimentary basins of the platform. Secondary stages were associated with oscillations of the global sea level.

Key words: *Silurian, fauna, flora, Siberia, type areas, biointervals.*

The Moiero, Turukhansk, and Noril'sk stratigraphic regions are referred to the type Silurian areas of East Siberia (Tesakov *et al.*, 1998; see the figure). In general, fauna and flora of the type areas are abundant and taxonomically diverse. Fossils are represented by graptolites, chitinozoans, acritarchs, cephalopods, trilobites, brachiopods, scolecodonts, conodonts, bryozoans, ostracodes, gastropods, crinoids, tetracorals, tabulates, heliolitids, stromatoporoids, tentaculitids, and eurypterids. Moreover, widespread stromatolite buildups and fucoids of various configuration enable the age determination of different bionomic zones of the basin. The deep-water facies with graptolites and shallow facies bearing fish remains are widespread in other East Siberian regions as well. These materials are beyond the type areas and our present discussion. Fauna and flora of the East Siberian type areas were previously considered in a series of stratigraphic and paleontological works (Abushik, 1960; Eltysheva, 1960; Nekhoroshev, 1961; Nikiforova and Andreeva, 1961; Vostokova, 1962; Maksimova, 1962; Ivanovskii, 1963; Myagkova *et al.*, 1963, 1977; Sokolov and Tesakov, 1963; Nikiforova, 1965; Myagkova, 1967; Lopushinskaya, 1976; Tesakov *et al.*, 1979, 1980, 1985, 1986, 1998a, 1998b, 1999, 2000; Sokolov (Ed.), 1982; Zaslavskaya, 1983; Tesakov (Ed.), 1983; Sheshegova, 1984) and in other papers. We present below a summary on species distribution among all faunal and floral groups encountered in the Silurian type areas of East Siberia (see the figure).

The distribution of species is given within regional chronozones. The quantity of specimens is designated as follows: (1) few; (2) rare; (3) common; (4) numerous; and (5) abundant. We illustrate the maximum size of encountered specimens. Large specimens are indicated by squares, medium-sized by circles, and small by octagons. The general stratigraphic ranges of species in type areas are indicated by black filling. The figure includes only those species, localities of which are reliably defined in one or another local and regional chronozones within a series of bed-by-bed correlated outcrops. Three hundred twenty one species are listed in the figure. They are arranged according to their appearance in chronozones. In each chronozone the species of a wide stratigraphic range are shown to the right, and those with limited stratigraphic ranges to the left. The levels of species appearance are marked as well. A faunal or floral group, to which a species is referred, is indicated by a symbol at the top of the figure. Below is a brief characteristic of local biointervals corresponding in stratigraphic range to local chronozones of the Silurian type areas of East Siberia. Each local biointerval is characterized by a list of species of concurrent range within a certain local chronozone. Biointervals are designated as follows: The seventh local biointerval—*Clorinda undata* (+)-(–) *Stricklandia salteri*. At the beginning, we place an index species of assemblages appearing in the local chronozone and mark it by "(+)". The next symbol "–" (dash) indicates

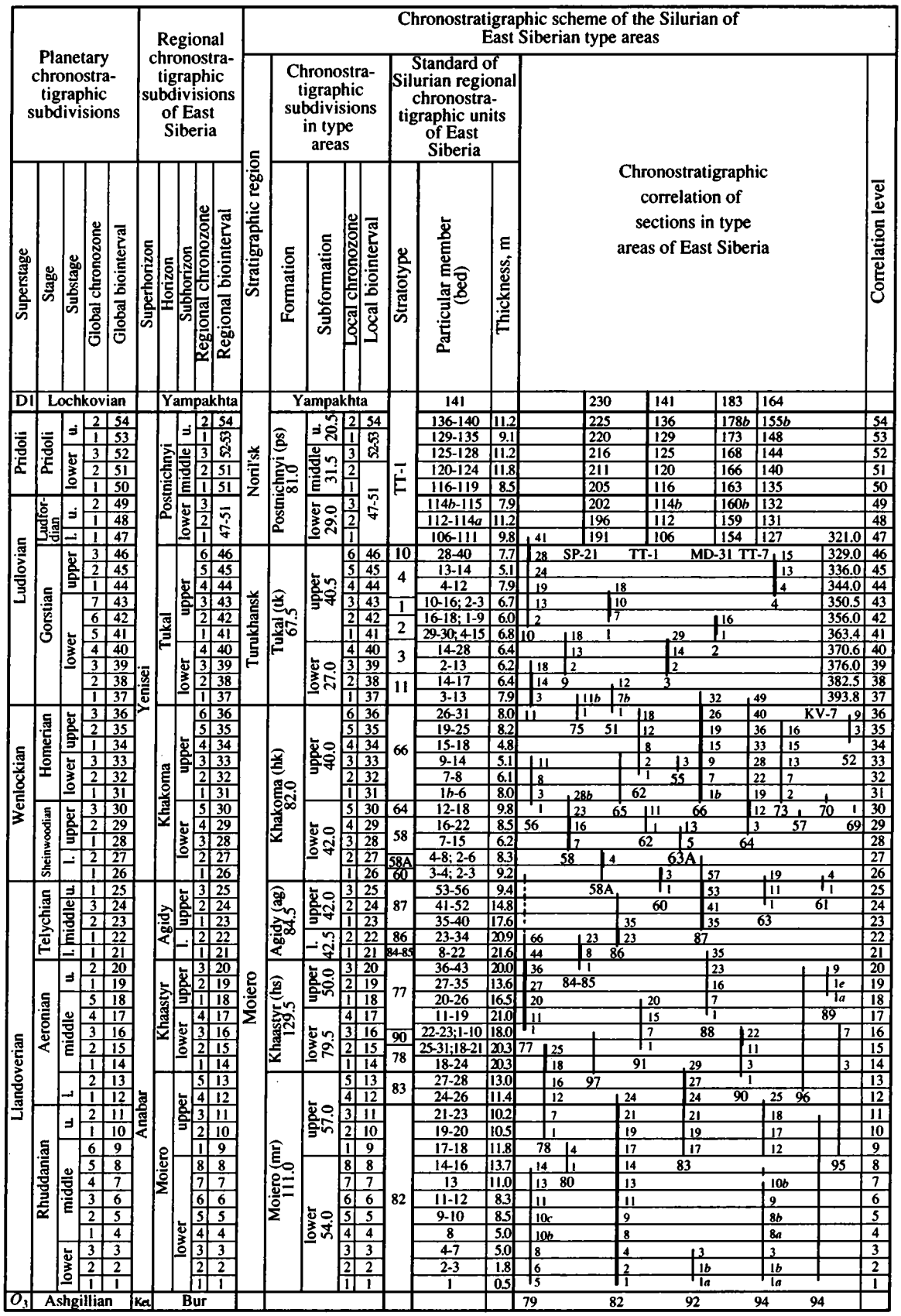

Planetary chronostratigraphic subdivisions
Regional chronostratigraphic subdivisions of East Siberia
Chronostratigraphic scheme of the Silurian of East Siberian type areas
Stratigraphic region
Chronostratigraphic subdivisions in type areas
Standard of Silurian regional chronostratigraphic units of East Siberia
Chronostratigraphic correlation of sections in type areas of East Siberia
Correlation level
Superstage
Stage
Substage
Global chronozone
Global biointerval
Superhorizon
Horizon
Subhorizon
Regional chronozone
Regional biointerval
Formation
Subformation
Local chronozone
Local biointerval
Stratotype
Particular member (bed)
Thickness, m
Yenisei
Anabar
Noril'sk
Turukhansk
Moiero
Lochkovian
Pridoli
Ludfordian
Gorstian
Homerian
Sheinwoodian
Telychian
Aeronian
Rhuddanian
Ashgillian
Yampakhta
Postnichnyi
Tukal
Khakoma
Khaastyr
Agidy
Moiero
Bur
Postnichnyi (ps) 81.0
Tukal (tk) 67.5
Khakoma (hk) 82.0
Agidy (ag) 84.5
Khaastyr (hs) 129.5
Moiero (mr) 111.0
upper 40.5
lower 27.0
upper 40.0
lower 42.0
upper 42.0
upper 50.0
lower 79.5
upper 57.0
lower 54.0
middle 31.5
lower 29.0
1. 42.5
47-51
52-53
141
136-140 11.2
129-135 9.1
125-128 11.2
120-124 11.8
116-119 8.5
114b-115 7.9
112-114a 11.2
106-111 9.8
28-40 7.7
13-14 5.1
4-12 7.9
10-16; 2-3 6.7
16-18; 1-9 6.0
29-30; 4-15 6.8
14-28 6.4
2-13 6.2
14-17 6.4
3-13 7.9
26-31 8.0
19-25 8.2
15-18 4.8
9-14 5.1
7-8 6.1
1b-6 8.0
12-18 9.8
16-22 8.5
7-15 6.2
4-8; 2-6 8.3
3-4; 2-3 9.2
53-56 9.4
41-52 14.8
35-40 17.6
23-34 20.9
8-22 21.6
36-43 20.0
27-35 13.6
20-26 16.5
11-19 21.0
22-23;1-10 18.0
25-31;18-21 20.3
18-24 20.3
27-28 13.0
24-26 11.4
21-23 10.2
19-20 10.5
17-18 11.8
14-16 13.7
13 11.0
11-12 8.3
9-10 8.5
8 5.0
4-7 5.0
2-3 1.8
1 0.5
TT-1
SP-21
MD-31
TT-7
KV-7

Figure.

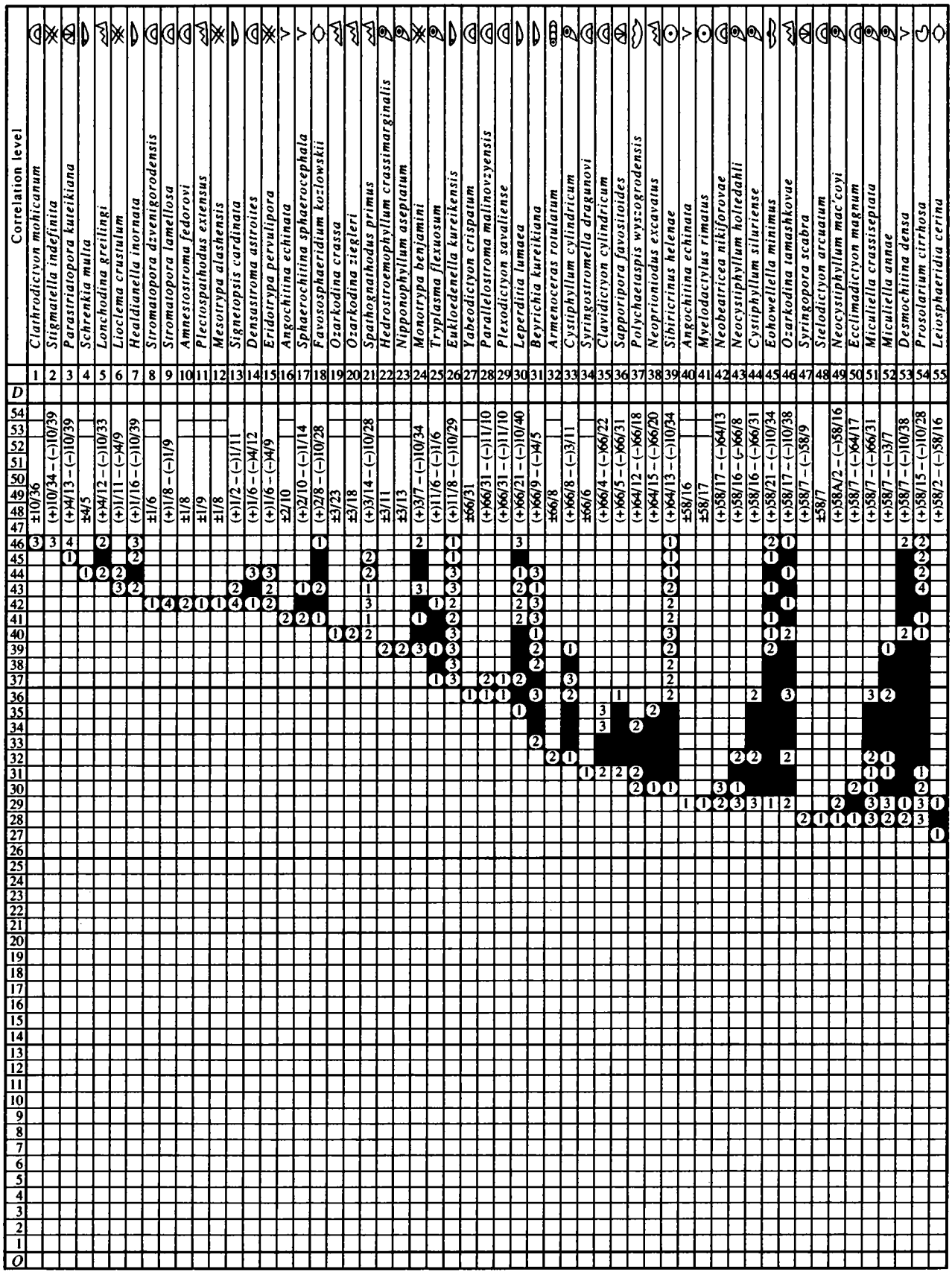

Correlation level
1 Clathrodictyon mohicanum ±10/36
2 Stigmatella indefinita (+)10/34 – (–)10/39
3 Parastriatopora kuteikiana (+)4/13 – (–)10/39
4 Schrenkia multa ±4/5
5 Lonchodina greilingi (+)4/12 – (–)10/33
6 Lioclema crustulum (+)1/11 – (–)4/9
7 Healdianella inornata (+)1/16 – (–)10/39
8 Stromatopora dzvenigorodensis ±1/6
9 Stromatopora lamellosa (+)1/8 – (–)1/9
10 Amnestostroma fedorovi ±1/8
11 Plectospathodus extensus ±1/9
12 Mesotrypa alashensis ±1/8
13 Signetopsis cardinata (+)1/2 – (–)1/11
14 Densastroma astroites (+)1/6 – (–)4/12
15 Eridotrypa pervulipora (+)1/6 – (–)4/9
16 Angochitina echinata ±2/10
17 Sphaerochitina sphaerocephala (+)2/10 – (–)1/14
18 Favososphaeridium kozlowskii (+)2/8 – (–)10/28
19 Ozarkodina crassa ±3/23
20 Ozarkodina ziegleri ±3/18
21 Spathognathodus primus (+)3/14 – (–)10/28
22 Hedrostroemophyllum crassimarginalis ±3/11
23 Nipponophyllum asepiatum ±3/13
24 Monotrypa benjamini (+)3/7 – (–)10/34
25 Tryplasma flexuosum (+)11/6 – (–)1/6
26 Eukloedenella kureikensis (+)11/8 – (–)10/29
27 Yabeodictyon crispatum ±66/31
28 Parallelostroma malinovzyensis (+)66/31 – (–)11/10
29 Plexodictyon savaliense (+)66/31 – (–)11/40
30 Leperditia lumaea (+)66/21 – (–)10/40
31 Beyrichia kureikiana (+)66/9 – (–)4/5
32 Armenoceras rotulatum ±66/8
33 Cystiphyllum cylindricum (+)66/8 – (–)3/11
34 Syringostromella dragunovi ±66/6
35 Clavidictyon cylindricum (+)66/4 – (–)66/22
36 Sapporipora favositoides (+)66/5 – (–)66/31
37 Polychaetaspis wyscogrodensis (+)64/12 – (–)66/18
38 Neoprioniodus excavatus (+)64/15 – (–)66/20
39 Sibiricrinus helenae (+)64/13 – (–)10/34
40 Angochitina echinata ±58/16
41 Myelodactylus rimatus ±58/17
42 Neobeatricea nikiforovae (+)58/17 – (–)64/13
43 Neocystiphyllum holtedahli (+)58/16 – (–)66/8
44 Cystiphyllum siluriense (+)58/16 – (–)66/31
45 Eohowellella minimus (+)58/21 – (–)10/34
46 Ozarkodina tamashkovae (+)58/17 – (–)10/38
47 Syringopora scabra (+)58/7 – (–)58/9
48 Stelodictyon arcuatum ±58/7
49 Neocystiphyllum mac'coyi (+)58A/2 – (–)58/16
50 Ecclimadictyon magnum (+)58/7 – (–)64/17
51 Miculiella crassisepiata (+)58/7 – (–)66/31
52 Miculiella annae (+)58/7 – (–)3/7
53 Desmochitina densa (+)58/7 – (–)10/38
54 Prosolarium cirrhosa (+)58/15 – (–)10/28
55 Leiosphaeridia cerina (+)58/2 – (–)58/16
D
O

Figure. (Contd.)

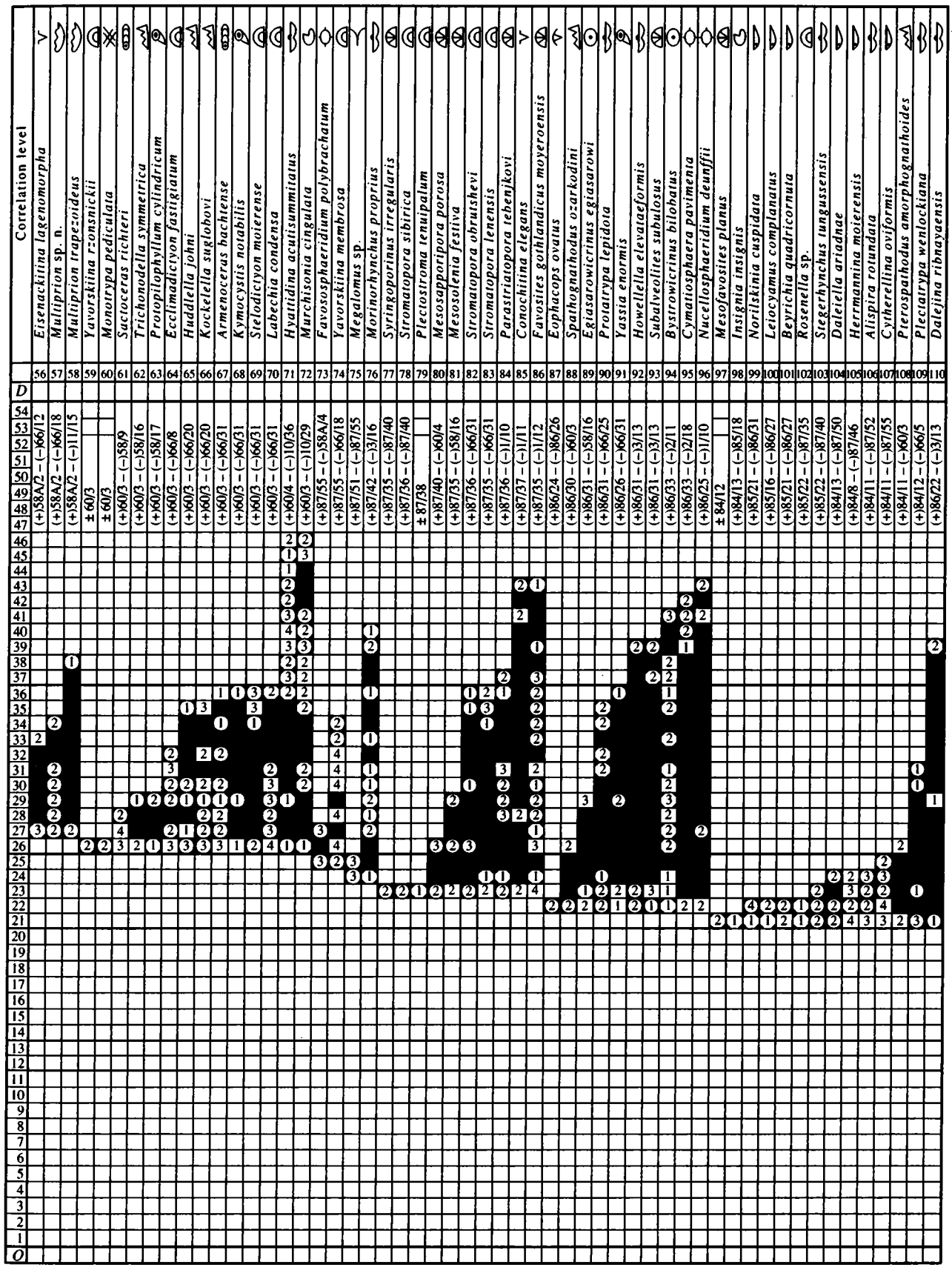


Figure. (Contd.)

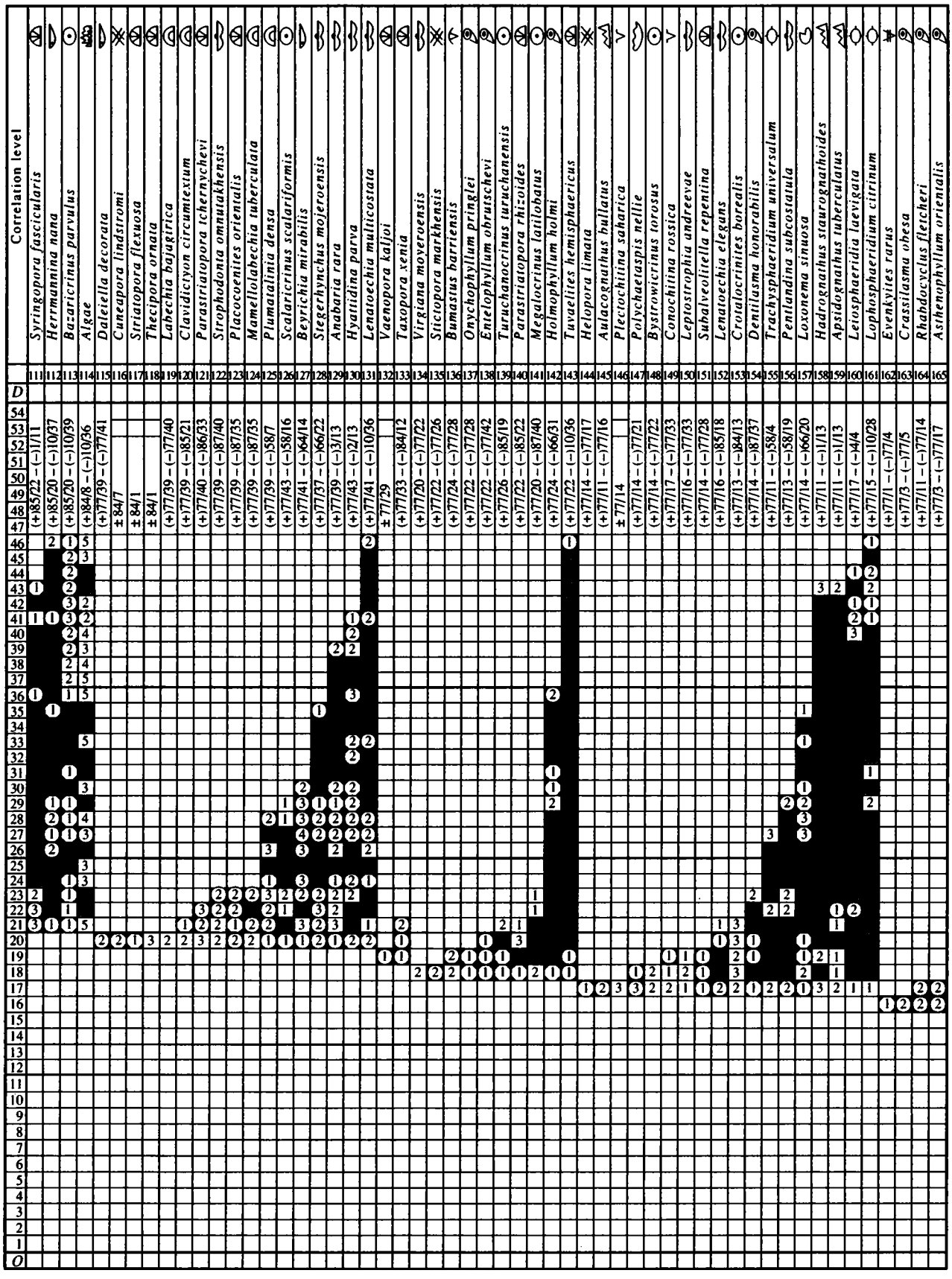

Correlation level
Syringopora fascicularis (+)85/22 – (–)1/11
Herrmannina nana (+)85/20 – (–)10/37
Bazaricrinus parvulus (+)85/20 – (–)10/39
Algae (+)84/8 – (–)10/36
Daleiella decorata (+)77/39 – (–)77/41
Cuneapora lindstromi ± 84/7
Siriatopora flexuosa ± 84/1
Thecipora ornata ± 84/1
Labechia bajagirica (+)77/39 – (–)77/40
Clavidictyon circumtextum (+)77/39 – (–)85/21
Parastriatopora tchernychevi (+)77/40 – (–)86/33
Strophodonta omnuiakhensis (+)77/39 – (–)87/40
Placocoenites orientalis (+)77/39 – (–)87/35
Mamellolabechia tuberculata (+)77/39 – (–)87/35
Plumatalinia densa (+)77/39 – (–)58/7
Scalaricrinus scalariformis (+)77/43 – (–)58/16
Beyrichia mirabilis (+)77/41 – (–)64/14
Stegerhynchus mojeroensis (+)77/37 – (–)66/22
Anabaria rara (+)77/39 – (–)3/13
Hyattidina parva (+)77/43 – (–)2/13
Lenatoechia multicostata (+)77/41 – (–)10/36
Vaenopora kaljoi ± 77/29
Taxopora xenia (+)77/33 – (–)84/12
Virgiana moyeroensis (+)77/20 – (–)77/22
Sticiopora markhensis (+)77/22 – (–)77/26
Bumastus barriensis (+)77/24 – (–)77/28
Onychophyllum pringlei (+)77/22 – (–)77/28
Entelophyllum obrutschevi (+)77/22 – (–)77/42
Turuchanocrinus turuchanensis (+)77/26 – (–)85/19
Parastriatopora rhizoides (+)77/22 – (–)85/22
Megalocrinus latilobatus (+)77/20 – (–)87/40
Holmophyllum holmi (+)77/24 – (–)66/31
Tuvaelites hemisphaericus (+)77/22 – (–)110/36
Helopora limaia (+)77/14 – (–)77/17
Aulacognathus bullatus (+)77/11 – (–)77/16
Plectochitina saharica ± 77/14
Polychaetaspis nellie (+)77/14 – (–)77/21
Bystrowicrinus torosus (+)77/14 – (–)77/22
Conochitina rossica (+)77/17 – (–)77/33
Leptostrophia andreevae (+)77/16 – (–)77/33
Subalveolitella repentina (+)77/14 – (–)77/28
Lenatoechia elegans (+)77/16 – (–)85/18
Crotalocrinites borealis (+)77/13 – (–)84/13
Denitiasma honorabilis (+)77/14 – (–)87/37
Trachysphaeridium universalum (+)77/11 – (–)58/4
Penilandina subcostatula (+)77/13 – (–)58/19
Loxonema sinuosa (+)77/14 – (–)66/20
Hadrognathus staurognathoides (+)77/11 – (–)1/13
Apsidognathus tuberculatus (+)77/11 – (–)1/13
Leiosphaeridia laevigata (+)77/17 – (–)4/4
Lophosphaeridium citrinum (+)77/15 – (–)10/28
Evenkyites rarus (+)77/1 – (–)77/4
Crassilasma obesa (+)77/3 – (–)77/5
Rhabdocyclus fletcheri (+)77/11 – (–)77/14
Asthenophyllum orientalis (+)77/3 – (–)77/17
D
O

Figure. (Contd.)

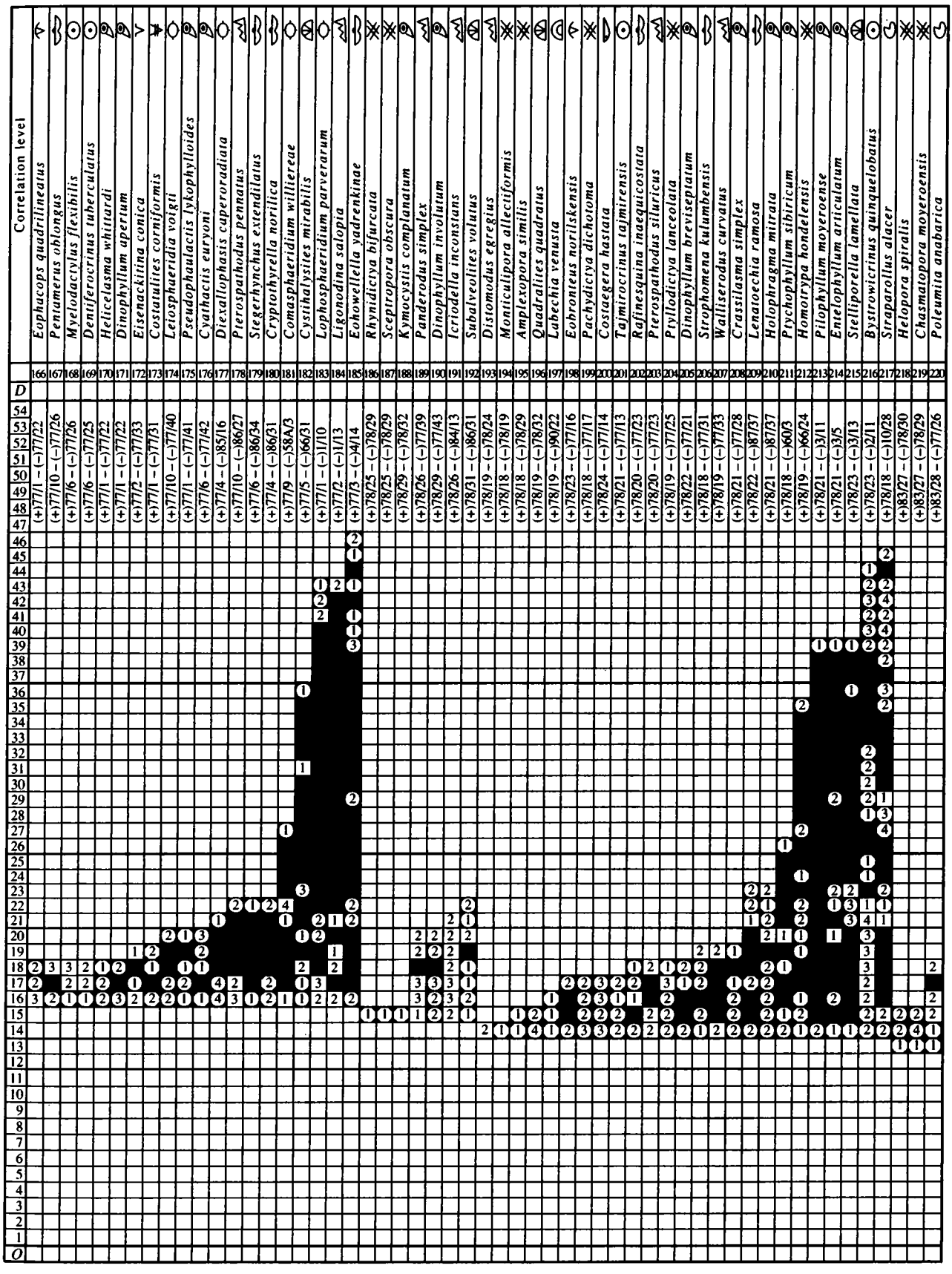
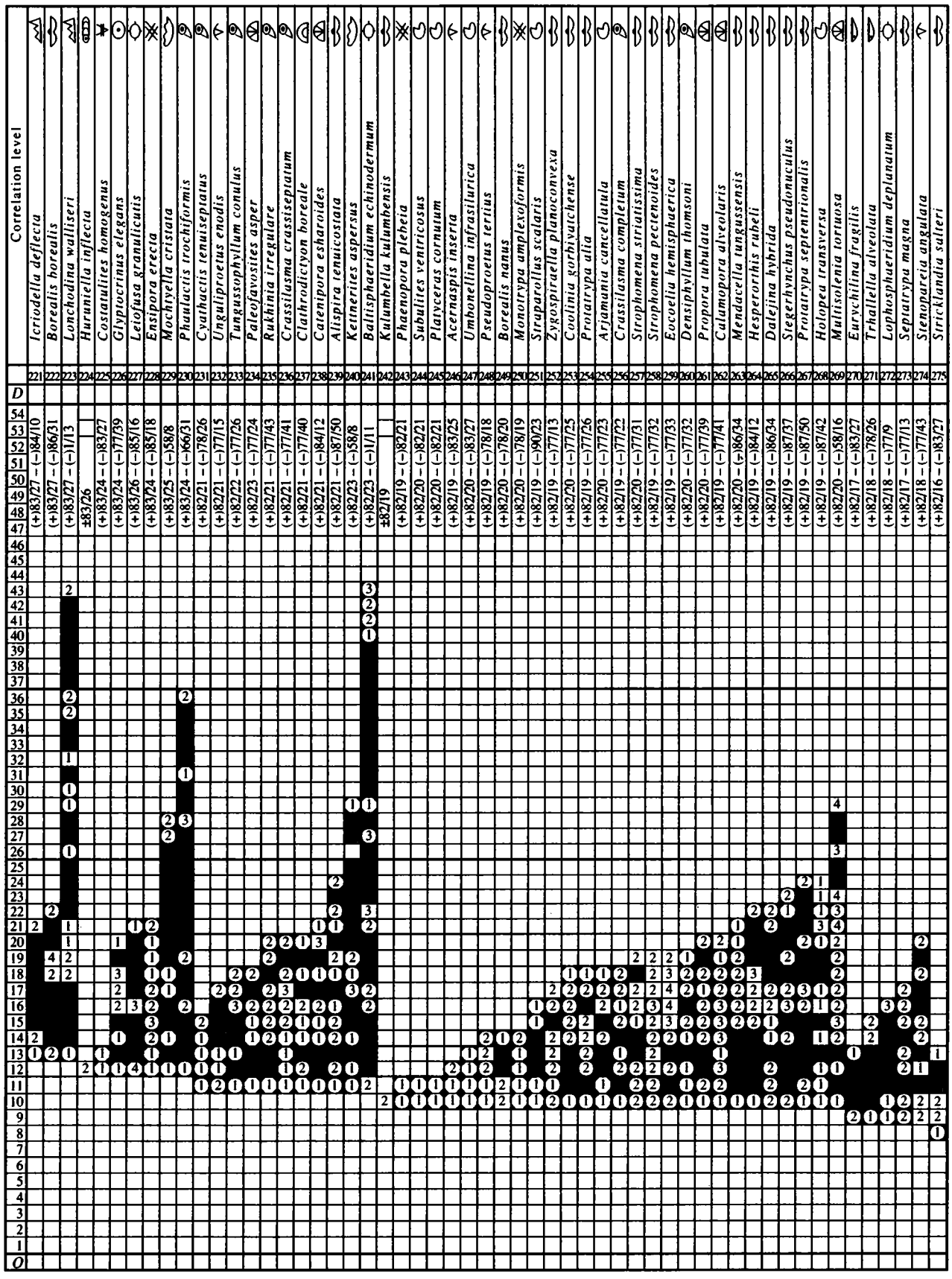


Figure. (Contd.)



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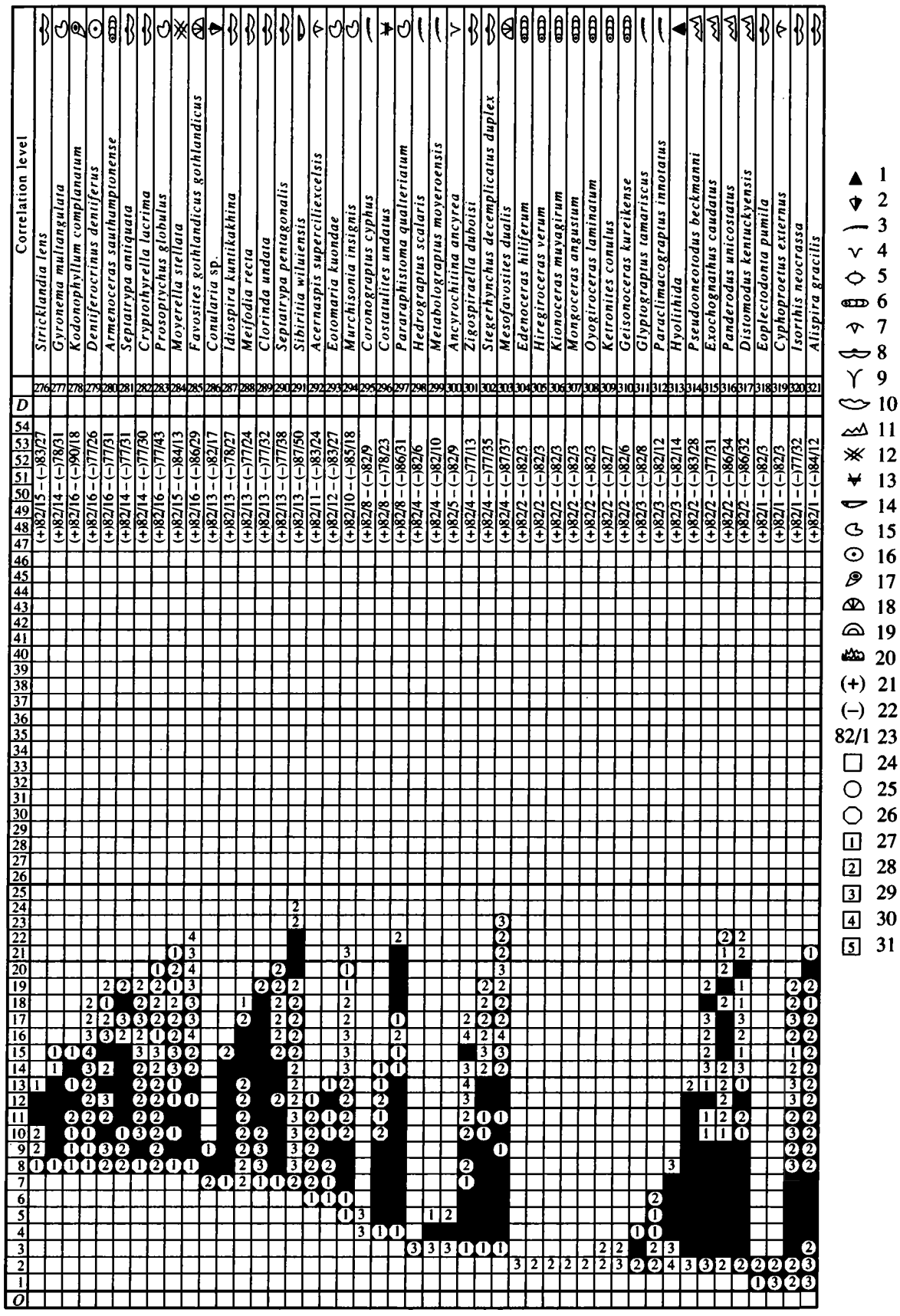

Figure. (Contd.)

an interval from the species appearance to disappearance. Finally, the symbol "(–)" is followed by an index species of assemblage disappearing in the local chronozone prior to its upper boundary. Species passing through a chronozone are not listed. Numbers of local biointervals accord with those of planetary biointervals. If the local unit corresponds to the planetary biointerval, their numbers coincide; if it is correlative with several planetary units, as in the uppermost Silurian, it has a double number; i.e., we place first the number of a lower planetary biointerval and, after a dash, the number of the upper one. Therefore, the numbers of local and planetary biointervals always coincide.

Presented below are characteristics of local biointervals of the Moiero, Kureika (Turukhansk), and Noril'sk stratigraphic type areas.

The lower Moiero Subformation (the lower–middle Rhuddanian) includes eight local biointervals (1–8).

1. The first local biointerval (first local chronozone $mr_{l(1)}$) *Alispira gracilis* (+)–(+) *Distomodus kentuckyensis* is characterized by appearance of three brachiopod and one trilobite species. Disappearing species are absent. The lower boundary is unconformable, and the upper Ashgillian sediments are missing from the section as a result of erosion. The base of the unit is correlated with the Silurian lower boundary corresponding to the base of the *acuminatus* biozone. The upper boundary is defined by appearance of numerous species of the second local biointerval.

2. The second local biointerval (second local chronozone $mr_{l(2)}$) *Distomodus kentuckyensis* (+)–(–) *Kionoceras muyagirum* is marked by appearance of seven cephalopod, three conodont, and two graptolite species, and by disappearance of five cephalopod, one brachiopod, and one trilobite forms. The species appearance and disappearance resulted from sharp facies changes. Initially, the basin was stagnant, with mass cephalopod burials, and subsequently deep-water shelf argillites with graptolite remains were accumulated. The majority of new forms had a wide stratigraphic range. Local and regional cephalopod species had limited distribution areas.

3. The third local biointerval (third local chronozone $mr_{l(3)}$) *Hedrograptus scalaris* (+)–(–) *Ketronites conulus* is marked by appearance of two graptolite, two brachiopod, one tabulate, and one chitinozoan species, and also by extinction of a graptolite and two cephalopod species. The appearance and disappearance of forms were associated with slight facies changes towards shoal sedimentation settings. The occurrence of tabulate and chitinozoan species that originated in the Ordovician is a result of the facies change.

4. The fourth local biointerval (fourth local chronozone $mr_{l(4)}$) *Coronograptus cyphus* (+)–(–) *Glyptograptus tamariscus* is distinguished by appearance of one graptolite, one tentaculitid, and one gastropod species, and by disappearance of one graptolite form. Most species are of wide stratigraphic range within limits of the Llandoverian. *C. cyphus* is the age-indicating species; its appearance level corresponds to the base of the planetary *cyphus* Zone. The appearance of species was associated with slight facies changes within the upper part of a deep shelf.

5. The fifth local biointerval (fifth local chronozone $mr_{l(5)}$) *Murchisonia insignis* (+)–(–) *Coronograptus cyphus* is marked by appearance of one gastropod species widespread in a uniform lithofacies, and by disappearance of two graptolite and one chitinozoan forms.

6. The sixth local biointerval (sixth local chronozone $mr_{l(6)}$) *Acernaspis supercilliexcelsis* (+)–(–) *Paraclimacograptus innotatus* is characterized by appearance of one widespread Llandoverian trilobite species and of one local gastropod form, and also by disappearance of one graptolite species. The appearance of species resulted from a facies change near the deep/shallow shelf boundary.

7. The seventh local biointerval (seventh local chronozone $mr_{l(7)}$) *Clorinda undata* (+)–(+) *Stricklandia salteri* is distinguished by appearance of four brachiopod and one ostracode species that are of a wide stratigraphic range within the Llandoverian. All species are regional, except for *C. undata* that became widespread beginning from the uppermost Rhuddanian. The species appearance was associated with slight facies changes within the lower shallow shelf.

8. The eighth local biointerval (eighth local chronozone $mr_{l(8)}$) *Stricklandia salteri* (+)–(+) *Septatrypa magna* begins at the appearance level of four brachiopod, two gastropod, one tetracoral, one crinoid, one cephalopod, one bryozoan, and one tabulate species. These forms are of wide stratigraphic range within the upper half of the Llandoverian. They had wide or local distribution areas. The species appearance resulted from slight facies changes in the lower shallow shelf. The appearance of *Favosites gothlandicus gothlandicus* and *Stricklandia lens* is close to the result of phylogenetic evolution.

The upper Moiero Subformation (the upper Rhuddanian-lower Aeronian) includes five local biointervals (9–13).

Chronozonal distribution of species and evolutionary stages of fauna and flora in biointervals of the Silurian type areas in East Siberia (the Moiero, Kureika, and Noril'sk stratigraphic areas): (1) heliolitids; (2) conulariids; (3) graptolites; (4) chitinozoans; (5) acritarchs; (6) cephalopods; (7) trilobites; (8) brachiopods; (9) fucoids; (10) scolecodonts; (11) conodonts; (12) bryozoans; (13) tentaculitids; (14) ostracodes; (15) gastropods; (16) crinoids; (17) tetracorals; (18) tabulates; (19) stromatoporoids; (20) stromatolites; (21) lower distribution limit; (22) upper distribution limit; (23) the number of an outcrop or borehole followed after a fraction sign by a bed number; (24) large fossils; (25) medium-sized fossils; (26) small fossils; (27) few specimens; (28) rare specimens; (29) common specimens; (30) numerous specimens; (31) abundant (rock-forming) specimens.

9. The ninth local biointerval (first local chronozone $mr_{2(1)}$) *Septatrypa magna* (+)–(+) *Eocoelia hemisphaerica* is marked by appearance of two ostracode, one acritarch, one brachiopod, and one trilobite species. The top of the biointerval is defined by the species appearance in the tenth local chronozone. All forms are regional and characteristic of the upper half of the Llandoverian. The disappearance and appearance of species at the lower boundary of the unit were associated with slight facies changes within the middle shallow shelf. *Trhallella alveolata* and *Eurychilina fragilis* are important for the unit base determination.

10. The tenth local biointerval (second local chronozone $mr_{2(2)}$) *Eocoelia hemisphaerica* (+)–(–) *Kulumbella kulumbensis* is characterized by appearance of thirteen brachiopod, six gastropod, three tabulate, and two bryozoan, two trilobite, and two tetracoral species, and by the extinction of one brachiopod species. Many of them are of wide stratigraphic and geographic ranges. The species appearance and disappearance at the lower boundary resulted from slight facies changes within the middle shallow shelf, though some of newly appeared forms are known from the Ordovician. The base of the local biointerval is defined by *Kulumbella kulumbensis, Borealis nanus, Eocoelia hemisphaerica,* and *Multisolenia tortuosa.*

11. The 11th local biointerval (third local chronozone $mr_{2(3)}$) *Alispira tenuicostata* (+)–(–) *Phaenopora plebeia* is distinguished by appearance of four tetracoral, two tabulate, one trilobite, one stromatoporoid, one brachiopod, one scolecodont, and one acritarch species, and also by disappearance of two gastropod and one bryozoan species. Most forms are widespread in the middle Llandoverian, but some are older or younger. The species are regional in general. The appearance and disappearance of forms at the lower boundary of the biointerval reflects small facies changes in the middle shallow shelf. The base of the biointerval is defined by *Paleofavosites asper.*

12. The 12th local biointerval (fourth local chronozone $mr_{2(4)}$) *Ensipora erecta* (+)–(–) *Acernaspis inserta* is noted for appearance of single cephalopod, tentaculitid, crinoid, acritarch, bryozoan, scolecodont, and tetracoral species, and also for disappearance of one cephalopod and one trilobite species. The forms are mainly characteristic of the upper half of the Llandoverian; they had regional distribution areas. The species appearance and disappearance at the base of the unit resulted from slight facies changes within the middle shallow shelf.

13. The 13th local biointerval (fifth local chronozone $mr_{2(5)}$) *Borealis borealis* (+)–(–) *Stricklandia salteri* is marked by the appearance of two gastropod, two brachiopod, and single tentaculitid, ostracode, and conodont species. Most forms occur only in the upper Llandoverian. Forms of limited and wide geographic areas are equally common. The species appearance and disappearance at the base of the biointerval associate with considerable facies changes in the area between the middle and upper shallow shelf. The lower boundary is defined by *Icriodella deflecta, Lonchodina walliseri,* and *Borealis borealis.*

The lower Khaastyr Subformation (the middle Aeronian) includes four local biointervals (14–17).

14. The 14th local biointerval (first local chronozone $hs_{1(1)}$) *Quadralites quadratus* (+)–(–) *Borealis nanus* is distinguished by appearance of six tetracoral, five bryozoan, three brachiopod, two tabulate, two crinoid, and single conodont, stromatoporoid, trilobite, ostracode, and gastropod species. The forms are of wide stratigraphic range within limits of the upper Llandoverian, Wenlockian, and even Ludlovian. They had wide or limited distribution areas. The appearance and disappearance of species at the lower boundary resulted from substantial facies changes in the middle–upper shallow shelf area. *Quadralites quadratus, Costaegera hastata,* and *Bystrowicrinus quinquelobatus* define the base of the biointerval.

15. The 15th local biointerval (second local chronozone $hs_{1(2)}$) *Icriodella inconstance* (+)–(–) *Quadralites quadratus* is noted for appearance of couples of bryozoan, tetracoral, and conodont species, and of one tabulate form. Disappearing here are five bryozoan, three tetracoral, and single tabulate, ostracode, gastropod, and brachiopod species. Most forms are of the Aeronian age. They had rather limited distribution areas. The species appearance and disappearance at the lower boundary associate with a substantial facies rearrangement within the upper shallow shelf. The base of the biointerval is defined by *Icriodella inconstans* and *Subalveolites volutus.*

16. The 16th local biointerval (third local chronozone $hs_{1(3)}$) *Cryptothyrella norilica* (+)–(–) *Crassilasma obesa* is marked by appearance of seven tetracoral, four brachiopod, four acritarch, two tentaculitid, two crinoid, two conodont, one trilobite, one chitinozoan, and one tabulate species. About a half of species was widespread from the uppermost Llandoverian to the Ludlovian. The species appearance and disappearance at the lower boundary resulted from slight facies changes within the middle shallow shelf. *Pentamerus oblongus, Myelodactylus flexibilis,* and *Cystihalysites mirabilis* are the markers of the biointerval base.

17. The 17th local biointerval (fourth local chronozone $hs_{1(4)}$) *Pentlandina subcostatula* (+)–(–) *Costaegera hastata* is characterized by appearance of conodont, brachiopod, and acritarch species triads in association with two chitinozoan, two crinoid, and single bryozoan, scolecodont, tabulate, tetracoral, and gastropod species. Disappearing from the unit are three brachiopod, two bryozoan, two tetracoral, two trilobite, and single conodont, chitinozoan, ostracode, crinoid, and gastropod species. The forms characteristic of the uppermost Llandoverian and Ludlovian are of wide or limited stratigraphic and geographic ranges. The appearance and disappearance of species at the lower

boundary associate with considerable facies changes in the middle shallow shelf.

The upper Khaastyr Subformation (the uppermost middle-upper Aeronian) includes three local biointervals (18–20).

18. The 18th local biointerval (first local chronozone $hs_{2(1)}$) *Tuvaelites hemisphaericus* (+)–(–) *Myelodactylus flexibilis* is distinguished by appearance of three tetracoral, two crinoid, two tabulate, one brachiopod, one bryozoan, and one trilobite species, and also by disappearance of six brachiopod, five tetracoral, three crinoid, two bryozoan, two gastropod, one trilobite, one conodont, and one tabulate species. These Llandoverian–Ludlovian forms are of wide or limited stratigraphic and geographic ranges. The species appearance and disappearance at the base of the biointerval resulted from slight facies changes in the middle shallow shelf. The lower boundary of the unit is defined by *Tuvaelites hemisphaericus.*

19. The 19th local biointerval (second local chronozone $hs_{2(2)}$) *Vaenopora kaljoi* (+)–(–) *Septatrypa antiquata* is noted for appearance of two tabulate forms and for disappearance of ten brachiopod, three tetracoral, two tabulate, two chitinozoan, two conodont, one trilobite, one tentaculitid, and one cephalopod species. The forms are characterized by either wide or limited stratigraphic and geographic ranges. The appearance and disappearance of species at the base of the unit associate with sharp facies changes at the boundary of the lower–middle shallow shelf.

20. The 20th local biointerval (third local chronozone $hs_{2(3)}$) *Anabaria rara* (+)–(–) *Panderodus simplex* reveals appearance of four tabulate, four stromatoporoid, four brachiopod, two ostracode, one bryozoan and one crinoid species. Disappearing from the interval are six tetracoral, four tabulate, two stromatoporoid, and single ostracode, bryozoan, acritarch, conodont, gastropod, brachiopod, crinoid, and trilobite species. These Llandoverian–Ludlovian species are of wide or limited stratigraphic and geographic ranges . The appearance and disappearance of species at the base of the unit resulted from a drastic facies change at the boundary of the middle and upper shallow shelf. *Daleiella decorata, Clavidictyon circumtextum, Placocoenites orientalis,* and *Anabaria rara* mark the base of the biointerval.

The lower Agidy Subformation (the lower–lower middle Telychian) includes two local biointervals (21–22).

21. The 21st local biointerval (first local chronozone $ag_{1(1)}$) *Pterospathodus amorphognathoides* (+)–(–) *Icriodella inconstans* is distinguished by appearance of eight ostracode, three brachiopod, two tabulate, one conodont, and one crinoid species, and by disappearance of three tabulate and three brachiopod species in association with stromatoporoid, crinoid, acritarch, conodont, bryozoan, and gastropod species pairs. These Llandoverian–Ludlovian forms are of wide or limited stratigraphic and geographic ranges. The appearance and disappearance of species associate with sharp facies changes corresponding to transition from the upper shallow shelf to lagoon environments. The base of the biointerval is defined by *Cytherellina oviformis, Pterospathodus amorphognathoides,* and *Hermannina nana.*

22. The 22nd local biointerval (second local chronozone $ag_{1(2)}$) *Spathognathodus ozarkodini* (+)–(–) *Distomodus kentuckyensis* is characterized by appearance of crinoid, brachiopod, and acritarch species pairs and also of single trilobite, conodont, and tetracoral representatives. Disappearing from the interval are five brachiopod, three ostracode, three tabulate, three conodont, one trilobite, and one gastropod species. Most forms are of wide stratigraphic range, occupying either wide or regional distribution areas. The species appearance and disappearance at the base of the biointerval resulted from sharp facies changes at the boundary between the upper and middle shallow shelf. *Spathognathodus ozarkodini* and *Subalveolites subulosus* define the lower boundary of the unit.

The upper Agidy Subformation (the upper middle–upper Telychian) includes three local biointervals (23–25).

23. The 23d local biointerval (first local chronozone $ag_{2(1)}$) *Mesosapporipora porosa* (+)–(–) *Lenatoechia ramosa* is distinct because of appearance of five tabulate, four stromatoporoid, and one chitinozoan species, and also by disappearance of four brachiopod, three tabulate, three stromatoporoid, one crinoid, and one tetracoral species. Most forms are characterized by a wide stratigraphic range within the Llandoverian- Ludlovian and by limited or wide distribution areas. The species appearance and disappearance at the base of the biointerval is connected with sharp facies changes in the middle–upper shallow shelf area. The lower boundary of the unit is marked by *Mesosolenia festiva* and *Mesosapporipora porosa.*

24. The 24th local biointerval (second local chronozone $ag_{2(2)}$) *Morinorhynchus proprius* (+)–(–) *Alispira tenuicostata* is distinguished by appearance of one brachiopod species and by disappearance of three ostracode, three brachiopod, and one gastropod species. The forms are mainly of a wide stratigraphic range within the upper Llandoverian and Wenlockian, and are characterized by regional distribution areas. The appearance and disappearance of species at the lower boundary of the biointerval resulted from slight facies changes within the upper shallow shelf.

25. The 25th local biointerval (third local chronozone $ag_{2(3)}$) *Yavorskiina membrosa* (+)–(–) *Cytherellina oviformis* is distinguishable because of appearance of single acritarch and stromatoporoid species, and also for disappearance of an ostracode form. The species are regional and characteristic of the upper Llandoverian and Wenlockian. Slight facies changes within the upper shallow shelf mark the base of the biointerval.

The lower Khakoma Subformation (the Sheinwoodian) includes five local biointervals (26–30).

26. The 26th local biointerval (first local chronozone $hk_{1(1)}$) *Huddlella johni* (+)–(–) *Pterospathodus amorphognathoides* is characterized by appearance of four stromatoporoid, three conodont, two nautiloid, two tetracoral, and single bryozoan, brachiopod, and gastropod species, and also by disappearance of single stromatoporoid, bryozoan, conodont, and tetracoral species. These Wenlockian species are of wide stratigraphic range and of wide or limited distribution areas. The base of the biointerval is marked by sharp facies changes at the boundary of the upper shallow shelf and coastal bar zone. The base of the unit is defined by *Ecclimadictyon fastigiatum, Labechia condensa*, and *Huddlella johni.*

27. The 27th local biointerval (second local chronozone $hk_{1(2)}$) *Multiprion trapezoideus* (+)–(–) *Trachysphaeridium universalum* is distinguished by appearance of two scolecodont, one acritarch, and one chitinozoan species, while three acritarch species disappeared from it. The forms are regional and show comparatively limited stratigraphic ranges. The base of the unit is marked by sharp facies changes within the shoal zone.

28. The 28th local biointerval (third local chronozone $hk_{1(3)}$) *Kockelella variabilis* (+)–(–) *Sactoceras richteri* is characterized by appearance of three tetracoral, two stromatoporoid, one tabulate, one chitinozoan, and one gastropod species. Two stromatoporoid and single tabulate, cephalopod, crinoid, and scolecodont species disappeared within this unit. The forms had limited distribution area, and their fairly wide stratigraphic ranges fall within the upper Llandoverian–Ludlovian time range. The lower boundary of the unit is marked by slight facies changes in the shoal area.

29. The 29th local biointerval (fourth local chronozone $hk_{1(4)}$) *Neocystiphyllum holtedahli* (+)–(–) *Trichonodella symmetrica* is noted for appearance of two tetracoral, and sole chitinozoan, crinoid, stromatoporoid, brachiopod, and conodont species; three crinoid, two tetracoral, two tabulate, and singular chitinozoan, acritarch, conodont, brachiopod, and scolecodont species disappeared here. These latest Llandoverian–Ludlovian forms are of wide or limited geographic and stratigraphic ranges. Slight facies changes that occurred in the shoal area are recorded at the lower boundary of the biointerval.

30. The 30th local biointerval (fifth local chronozone $hk_{1(5)}$) *Neoprioniodus excavatus* (+)–(–) *Neobeatricea nikiforovae* is marked by appearance of single scolecodont, conodont, and crinoid species, and by disappearance of two stromatoporoid and one ostracode forms. Most species are of limited stratigraphic and local geographic ranges. The base of the unit associate with comparatively sharp facies changes within the shoal zone.

The upper Khakoma Subformation (the Homerian) includes six local biointervals (31–36).

31. The 31st local biointerval (first local chronozone $hk_{2(1)}$) *Ozarkodina excavata* (+)–(–) *Plectatrypa wenlockiana* is characterized by appearance of two stromatoporoid, one tabulate, and one conodont species, and by disappearance of singular stromatoporoid and brachiopod species. All forms show rather limited stratigraphic ranges within the Wenlockian; they had local or regional distribution areas. The appearance and disappearance of species at the base of the unit associate with sufficiently drastic facies changes in the shoal area. The lower boundary of the biointerval is defined by *Ozarkodina excavata* and by *Sapporipora favositoides* known from Siberia and Japan.

32. The 32nd local biointerval (second local chronozone $hk_{2(2)}$) *Cystiphyllum cylindricum* (+)–(–) *Ecclimadictyon fastigiatum* is marked by appearance of one cephalopod and one tetracoral species, and also by disappearance of sole cephalopod, tetracoral, and stromatoporoid species. The forms had limited distribution areas showing wide or limited stratigraphic ranges within the Wenlockian and Ludlovian. The species appearance and disappearance at the base of the unit associate with slight facies changes in the shoal area.

33. The 33d local biointerval (third local chronozone $hk_{2(3)}$) *Beyrichia kureikiana* (+)–(–) *Eisenackitina lagenomorpha* is distinguished by appearance of one ostracode and by disappearance of one chitinozoan species. The species are local and limited in stratigraphic range within the Wenlockian. The appearance and disappearance of forms at the lower boundary of the unit resulted from slight facies changes in the shoal area.

34. The 34th local biointerval (fourth local chronozone $hk_{2(4)}$) *Eisenackitina lagenomorpha* (–)–(–) *Alispira rotundata* is recognized between disappearance of one chitinozoan form and disappearance of two scolecodonts, and sole brachiopod, stromatoporoid, and gastropod species. Most forms are of limited stratigraphic and geographic ranges.

35. The 35th local biointerval (fifth local chronozone $hk_{2(5)}$) *Leperditia lumaea* (+)–(–) *Huddlella johni* is marked by appearance of one ostracode species and by disappearance of three conodont, two brachiopod, and singular stromatoporoid, gastropod, and bryozoan species. The forms are mainly regional and show comparatively limited ranges within the Wenlockian and Ludlovian. Slight facies changes within the shoal zone are recorded at the base of the biointerval.

36. The 36th local biointerval (sixth local chronozone $hk_{2(6)}$) *Plexodictyon savaliense* (+)–(–) *Cystihalysites mirabilis* is noted for appearance of three stromatoporoid forms and for disappearance of six tetracoral, five stromatoporoid, two tabulate, and one cephalopod species. The forms are characteristic of the Wenlockian-Ludlovian period. Their geographic ranges were limited or fairly wide. The base of the unit is marked by slight facies changes within the shoal zone.

The lower Tukal Subformation (lower part of the lower Gorstian) includes four local biointervals (37–40).

37. The 37th local biointerval (first local chronozone $tk_{1(1)}$) *Tryplasma flexuosum* (+)–(–) *Parallelostroma malinovzyensis* is distinguished by appearance of one tetracoral and one ostracode species, and also by disappearance of two stromatoporoid and one tabulate species. The forms are mainly regional and typical of the Wenlockian-Ludlovian time range. The base of the biointerval is marked by drastic facies changes at the boundary between the shoal and off-shoal areas.

38. The 38th local biointerval (second local chronozone $tk_{1(2)}$) *Parastriatopora tebenjkovi* (–)–(–) *Multiprion trapezoideus* is marked by species that disappeared in the 37th local biointerval and by additional disappearance of one scolecodont form. Slight facies changes within the off-shoal area mark the lower boundary of the unit.

39. The 39th local biointerval (third local chronozone $tk_{1(3)}$) *Nipponophyllum aseptatum* (+)–(–) *Anabaria rara* is characterized by appearance of two tetracoral and one bryozoan species, and also by disappearance of six tetracoral, three brachiopod, and two tabulate species. Most forms are local or regional, having limited or wide ranges within the Wenlockian–Ludlovian. The base of the unit is marked by significant facies changes at the boundary of the closed and open shelf.

40. The 40th local biointerval (fourth local chronozone $tk_{1(4)}$) *Spathognathodus primus* (+)–(–) *Morinorhynchus proprius* is noted for appearance of three conodont forms and for disappearance of two conodont and one brachiopod species. The forms of the latest Wenlockian-Ludlovian time had rather limited distribution areas. Sharp facies changes at the open/closed shelf boundary are recorded at the base of the biointerval.

The upper Tukal Subformation (the terminal lower–upper Gorstian) includes six local biointervals (41–46).

41. The 41st local biointerval (first local chronozone $tk_{2(1)}$) *Angochitina echinata* (+)–(–) *Hyattidina parva* is marked by appearance of two chitinozoan and one acritarch species, whereas single chitinozoan, crinoid, and brachiopod species disappeared here. Most forms are regional, having wide stratigraphic ranges within the Wenlockian and Ludlovian. The base of the unit associate with fairly sharp facies changes at the open/closed shelf boundary.

42. The 42nd local biointerval (second local chronozone $tk_{2(2)}$) *Mesotrypa alashensis* (+)–(–) *Cymatiosphaera pavimenta* is distinguished by appearance of four stromatoporoid, two bryozoan, and one conodont and ostracode species, and by disappearance of four conodont, three stromatoporoid, and sole bryozoan, tetracoral, and acritarch species. Most forms are of rather limited geographic and stratigraphic ranges within the Ludlovian. The base of the biointerval is marked by sharp facies changes at the boundary of the open and closed shallow shelf.

43. The 43d local biointerval (third local chronozone $tk_{2(3)}$) *Lioclema crustulum* (+)–(–) *Hadrognathus staurognathoides* is characterized by appearance of one bryozoan and one ostracode species, whereas disappearing here are four conodont, three acritarch, two chitinozoan, two tabulate, and one ostracode forms. Most of species are of wide geographic and stratigraphic ranges within the Wenlockian-Pridoli time range. The base of the unit is marked by sharp facies changes at the boundary of the closed and open shelf.

44. The 44th local biointerval (fourth local chronozone $tk_{2(4)}$) *Schrenkia multa* (+)–(–) *Leiosphaeridia laevigata* is marked by appearance of one ostracode and one conodont species; two ostracode and singular stromatoporoid, bryozoan, acritarch, and crinoid species disappeared in the chronozone. Most forms are regional, mainly characteristic of the Wenlockian and Ludlovian. The appearance and disappearance of species at the base of the unit associate with fairly sharp facies changes at the boundary of the open and closed shelf. The base of the biointerval is defined by *Schrenkia multa.*

45. The 45th local biointerval (fifth local chronozone $tk_{2(5)}$) *Parastriatopora kureikiana* (+)–(–) *Spathognathodus primus* is distinguished because of the mass appearance of one branching tabulate species that is followed by disappearance of one conodont and one gastropod species. The species are characterized by a limited stratigraphic range in the Ludlovian and by limited or wide distribution areas. The lower boundary of the biointerval is marked by sharp facies changes within the semiclosed shelf.

46. The 46th local biointerval (sixth local chronozone $tk_{2(6)}$) *Clathrodictyon mohicanum* (+)–(–) *Parastriatopora kureikiana* corresponds to the time range of appearance of sole stromatoporoid and bryozoan species. Disappearing here are four ostracode and four brachiopod forms, bryozoan, tabulate, conodont, acritarch, crinoid, and gastropod species pairs, as well as one stromatoporoid and one chitinozoan species. These forms of the Ludlovian–Pridoli time are characterized by wide or limited geographic and stratigraphic ranges. The species appearance and disappearance at the base of the unit coincide with sharp facies changes within the closed and semiclosed shelf zone. The upper boundary of the biointerval is marked by the disappearance of 22 species of different faunal and floral groups in response to transition from lagoonal-marine to halogenic facies of a closed shelf that is traceable throughout the Siberian platform.

The Postnichnyi Formation (the Ludfordian–Pridoli) is the stratotype of the Postnichnyi Horizon, and its sediments yield few poorly preserved organic remains identifiable only at a generic level. Therefore, we consider for this part of the section the local biointervals of the Sharino Formation of Taimyr accepting it

for parastratotype of the Postnichnyi Horizon in East Siberia. The type section of the Sharino Formation is situated at the Nizhnyaya Taimyra River in the vicinity of the Middendorf Caves, Exposure 218 (Tesakov *et al.*, 1995).

The lower Sharino Subformation (the Ludfordian) includes two local biointervals (47, 48–49).

47. The 47th local biointerval (first local chronozone $sh_{1(1)}$) *Bohemograptus bohemicus* (–)–(–) *Monograptus priodon* is characterized by disappearance of two graptolite and two brachiopod species at the base, and of two graptolite forms at the top of the unit. The species had comparatively wide distribution areas, and their stratigraphic ranges are known within the Ludlovian–Pridoli. The base of the biointerval is marked by significant facies changes at the boundary of the deep and shallow shelf.

48–49. The 48th–49th local biointervals (second and third local chronozones $sh_{1(2-3)}$) *Monograptus priodon* (–)–(+) *Monograptus rarus* are noted for disappearance of two graptolite forms and for the appearance of two graptolite species. The forms are of rather limited Ludfordian–Pridoli stratigraphic range. The lower boundary of the units is marked by slight facies changes within the uppermost deep shelf.

The middle and upper Sharino subformations (the Pridoli) include three local biointervals (50, 51, 52–54).

50. The 50th local biointerval (first local chronozone of the middle Sharino Subformation $sh_{2(1)}$) *Monograptus rarus* (+)–(–) *Hemicosmorthoceras semiannulatum* is distinguished by appearance of two graptolite species and by disappearance of two cephalopod species. The forms are of unclear stratigraphic range, having fairly limited distribution areas. The base of the biointerval is marked by sharp facies changes at the boundary between the lowermost shallow and the deep shelf.

51. The 51st local biointerval (second local chronozone of the middle Sharino Subformation $sh_{2(2)}$) *Hemicosmorthoceras semiannulatum* (–)–(–) *Monograptus rarus* is characterized by species of unclear and limited stratigraphic ranges, which had comparatively limited distribution areas. The base of the unit is marked by slight facies changes within the deep shelf.

52–54. The 52nd-54th local biointervals (third local chronozone of the middle–upper Sharino subformations $sh_{2(3)}$–$sh_{3(1-2)}$) *Monograptus rarus* (–)–(+) *Favosites kozlowskii* represent an interzone barren of fossil remains. Its top coincides with the Silurian–Devonian boundary defined by tabulates in East Siberia, namely by appearance of *Favosites kozlowskii, Tiverina vermiculata, Parastriatopora fallacis*, and *Scalites prostratus* in the Igarka region (Sokolov, Ed., 1982: Tesakov *et al.*, p. 24; Tesakov, p.114), by appearance of *Tiverina vermiculata* in the Ledyanaya River region, and by appearance of *Favosites kozlowskii, F. socialis*, and *Scalites prostratus* in Taimyr (Tesakov *et al.*, 1995).

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Reviewer B.S. Sokolov

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The Reference Section of the Lower–Upper Permian Boundary Beds in the Verkhoyansk Region and Its Correlation

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Abstract—The following Lower–Upper Permian brachiopod zonation is established in the Baraiy River basin (the western Verkhoyansk region): (1) the *Megousia kuliki* Zone bearing the associated *Neouddenites–Tumaroceras yakutorum* goniatite assemblage, (2) the *Kolymaella ogonerensis* Zone containing the *Baraioceras–Tumaroceras kashirzevi* ammonoid assemblage, (3) the *Mongolosia russiensis* Zone with the *Daubichites–Sverdrupites harkeri* ammonoid assemblage, (4) the *Olgerdia zavodovskyi* Zone, and (5) the *Cancrinelloides obrutshevi* Zone. The boundary between the Kungurian Stage of the Lower Permian and the Ufimian Stage of the Upper Permian is drawn at the base of the *Kolymaella ogonerensis* Zone of the Tumara Horizon. The most distinct biostratigraphic level is the base of the *Mongolosia russiensis* Zone, which corresponds to the lower Roadian boundary. The compatibility analysis of Permian biotic and abiotic events in the western Verkhoyansk region shows that the *Mongolosia russiensis* and *Cancrinelloides obrutshevi* zones correspond to phases of the highest sea level stand, which has determined ranges of the zones. The Baraiy River section can be accepted for the reference one in the Verkhoyansk region. It may also facilitate correlation of the Uralian and North American stage scales.

Key words: *Permian, Tumara Horizon, Delenzha Horizon, Kungurian Stage, Ufimian Stage, goniatites, brachiopods, zone, Verkhoyansk region.*

INTRODUCTION

The Permian rock succession in the Baraiy River basin of the Verkhoyansk region attracts a considerable interest because of many factors. First, it represents a continuous, stratigraphically complete, and well-exposed section of simple geological structure. Second, in the Baraiy structural–lithologic subzone, the Permian sections are predominantly composed of marine facies that yield goniatites, brachiopods, and bivalves. Third, stratotypes and parastratotypes of local and regional stratigraphic units that have been recognized within this basin are unambiguously correlated to the Delenzha and Dulgalakh sections of the Eastern Kuranakh structural–lithologic subzone. The latter are located in the stratotype area of the Permian horizons of the Verkhoyansk region (*Resheniya...*, 1982). Fourth, it should be stressed that the Baraiy River section was examined by many experts on biostratigraphy who study the Upper Paleozoic deposits of the Verkhoyansk region and northeastern Russia (Andrianov, 1966, 1975, 1985; Abramov *et al.*, 1973; Abramov, 1974; Abramov and Grigor'eva, 1988; Solomina, 1988, 1997; Grinenko *et al.*, 1997).

The variety of views on the regional stratigraphic units can be reduced to two. One is viewpoint of Abramov who correlates the Tumara Formation of the western Verkhoyansk region, which is used to distinguish the Tumara Horizon, with the Upper Permian Omolon Horizon, whereas many others consider it as correlative to the Lower Permian Dzhigdala Horizon of Northeastern Russia. Exactly this contradiction made us to take up the pen, because the first, less common view on the Lower–Upper Permian boundary deposits of the Verkhoyansk region (Abramov and Grigor'eva, 1988) was not doubted for ten years and led to miscorrelations of regional bio- and lithostratigraphic units with those of the standard scale. The last point is of great importance for editing geological maps and legends of various kind.

Resolutions of the International Subcommission on Permian Stratigraphy and Second Guadalupian Symposium (Yugan Jin, 1996; Leven *et al.*, 1997), which introduce the Guadalupian Series of the Permian System in practice, necessitate the spare criteria retrieval in order to correlate the Uralian stratotype sections with North American standards. The western Verkhoyansk

region is favorable in this aspect, as it is of transitional type and hosts mixed faunas (Budnikov *et al.*, 1994, 1995, 1996). In addition, new data that can substantiate the reliable correlation became recently available from both the Verkhoyansk region (Grinenko *et al.*, 1997) and the North Uralian Province (Bogoslovskaya, 1997) and adjacent areas (Kotlyar *et al.*, 1997). The idea to consider the Tumara goniatite assemblage of the Verkhoyansk region as endemic gradually changes, and index-species of brachiopod zones established in the Verkhoyansk–Kolyma area have been found recently in the North Uralian Province (Ganelin, 1997).

HISTORY OF THE PROBLEM AND FACTUAL DATA

Let us consider the crux of the problem in three aspects corresponding to three classic components of common stratigraphic work. A complex of questions, misinterpretations and different views appears in the course of (1) subdivision of a geological section, (2) subsequent correlation of individual sections (in our case, those of the Verkhoyansk–Okhotsk Province), and (3) dating of the distinguished units, or, what is the same, of their correlation with the stratotype units of the standard scale. The Verkhoyansk terrigenous complex is known to be poor in fossils, and this impedes solution of stratigraphic problems. Accordingly, the main tasks of this work were as follows: (1) to establish the structure and biostratigraphic succession of the Lower–Upper Permian boundary beds in the Baraiy structural–lithologic subzone of the Verkhoyansk region, where one can expect to observe the most complete Permian sections that have been accumulated in close proximity to marine settings; (2) to refine the Permian biostratigraphy in the Baraiy River basin and to better substantiate its correlation with the Permian type sections of the Kolyma–Omolon massif and with successive type zones of the Biarmian paleogeographic province; (3) to define more precisely the possible correspondence between the regional and standard stratigraphic units by means of ranging main biotic and abiotic events.

Those researchers who studied the western Verkhoyansk in various periods elaborated several biostratigraphic schemes based on ammonoids, brachiopods, and bivalves (Andrianov, 1975; Abramov and Grigor'eva, 1988; Solomina, 1997; Kurushin *et al.*, 1996; and others). Each of them suggested their own, though similar correlation schemes of the western Verkhoyansk and other region sections of the Verkhoyansk–Okhotsk Province. As is mentioned, the third task of stratigraphy (dating of deposits) is correlation of successive regional biostratigraphic units with those of the international stratigraphic scale. Goniatites represent the only orthostratigraphic group among other faunas of Verkhoyansk region, which can be most effectively used for such a correlation. After works by Ruzhentsev (1961), Andrianov (1966), and Popov (1970), ammonoids became the main faunal group usable for dating of deposits and for correlating them with Permian marine sections of the globe. The correlation potential of ammonoids was convincingly demonstrated in the fundamental work by Andrianov (1985). Their stratigraphic significance in the Verkhoyansk region is limited however because of sporadic occurrence in Permian deposits, and some benthic faunas, e.g., brachiopods, foraminifers, and bivalves, appeared to be quite important here.

As mentioned above, considerably different viewpoints appear in the course of biostratigraphic correlation of individual regional sections, and subsequently, by their correlation with well-studied sequences of the adjacent Kolyma–Omolon massif. Precisely this is the main goal of this work in addition to the analysis of real biostratigraphic succession. As for the Lower–Upper Permian boundary, it was formerly drawn (*Resheniya...*, 1982) between the Tumara and Delenzha horizons of the Verkhoyansk region, which were correlated respectively with the Dzhigdala and Omolon horizons of the Kolyma–Omolon massif. This view was accepted widely (Ganelin, 1984; Andrianov, 1975, 1985; Klets, 1995; Kotlyar, 1996; Solomina, 1997), but Abramov and Chernyak had different opinions, though apart from the interregional correlation. The Lower–Upper Permian boundary was placed by Abramov (1974) at the base of the Dasaknya Horizon and by Chernyak (1975) at the base of the Dzhigdala Horizon. In other words, they suggested that the Upper Permian begins with the Kungurian Stage. This view gained lesser recognition, though it touched upon problems of interregional correlation, which have no unambiguous solution, as we believe, even in the other approach having a wider support.

The correlation between the Permian deposits of the East Kuranakh (the Endybal and Tumara river basins) and Baraiy (the Baraiy River basin) subzones is of extreme significance not only for the Verkhoyansk region but also for entire Northeastern Russia, because stratotypes and parastratotypes of the regional stratigraphic units are located here. This is one of the subjects of the present work. Abramov and Grigor'eva (1988) proposed the modified Permian stratigraphic scheme for the Verkhoyansk region, in which they suggested older ages of the Mugochan and Nyunegi formations than those accepted before (Abramov *et al.*, 1973, Abramov, 1974) . Main distinctions of the new Permian stratigraphic scheme (Abramov and Grigor'eva, 1988, p. 87) from that accepted at the Conference on Regional Stratigraphy (*Resheniya...*, 1982) are as follows: (1) the Delenzha Formation of the Tumara River section is considered as an equivalent of the Mol Formation at the level of the Gizhiga Horizon of the Baraiy River section; (2) the Tumara Formation of the Tumara River section is correlated with the united Mugochan and Nyunegi formations. Earlier (Abramov *et al.*, 1973, p. 115), it was stated that "the Mugochan Formation corresponds to the Lower Delenzha Subformation" and

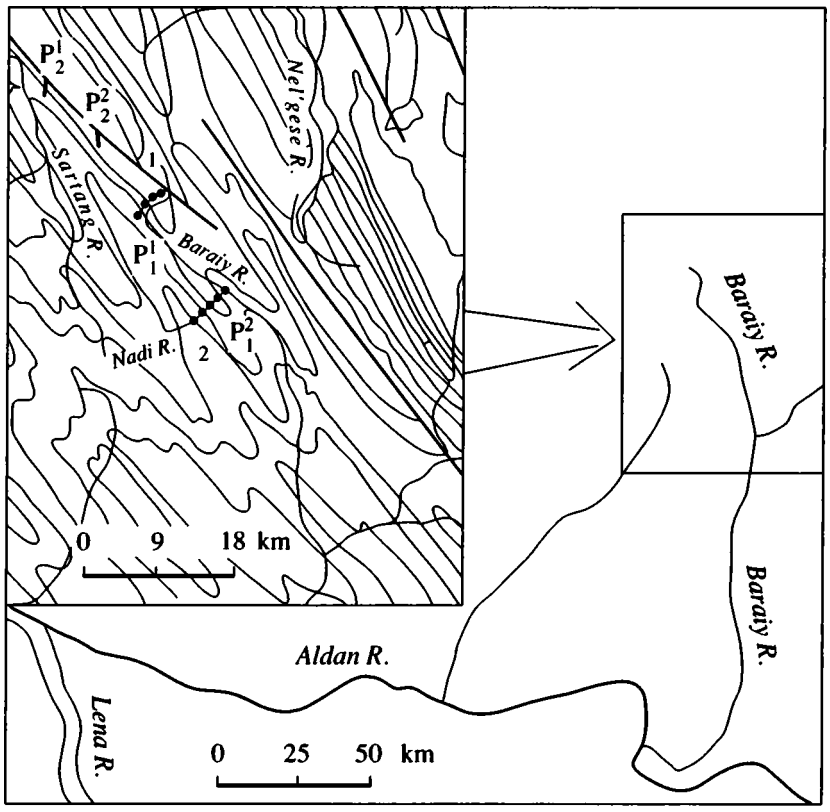


Fig. 1. Geographic position of the Baraiy (1) and Nadi (2) sections.

"the Nyunegi Formation corresponds to the Upper Delenzha Subformation". There is also an intermediate variant of the scheme (Abramov, 1974).

Another Permian biostratigraphic scheme for the Verkhoyansk region was suggested by Solomina (1997) who was one of co-authors of the work published in 1973. She distinguished the Mugochan and Nyunegi horizons on the basis of stratotypes of corresponding formations in the Baraiy River basin but retained the correlation between the Delenzha and Tumara formations of the Delenzha and Tumara river sections as it was in the scheme of 1973.

Our work is based on the results of the large-scale geological mapping and lithological–biostratigraphic investigations in the Baraiy River basin during the field seasons of 1982 and 1992–1994. We studied sections along the Baraiy River and its large tributary Nadi River (Figs. 1 and 2), which include stratotypes or parastratotypes of stratigraphic units mentioned above. We obtained new stratigraphic materials and collected abundant paleontological remains. Following Andrianov (1985) and Solomina (1997), we believe that the western Verkhoyansk area and the Baraiy River sections can be accepted for reference area and section enabling correlation between the northern, western, southern and southeastern parts of the whole Verkhoyansk region and also for remote correlations. We suggest a modified scheme, which is similar to that of Solomina (1997) but includes different regional subdivisions of a higher correlation potential. The succession of horizons corresponds to that suggested by Andrianov (1975), and biostratigraphy is based on distribution of brachiopods and ammonoids. Unlike Solomina (1997), we use traditional names of the regional stratigraphic units (Andrianov, 1975; *Resheniya...*, 1982). Most biostratigraphic zones were originally recognized by Ganelin (1984, 1990), and the *Olgerdia zavodovskyi* Zone was distinguished by Solomina (1989, 1997). The inferred relationships between the Uralian, regional, and local stratigraphic units are summarized in Table 1.

Fossils, except for those especially indicated, were identified by Klets (brachiopods), Kutygin (ammonoids), Sosipatrova (foraminifers, 1983), Boiprav (bivalves), and Gorelova (flora). We used the ammonoid collection of Andrianov, some specimens of which were reclassified by Kutygin.

BIOSTRATIGRAPHY

The Baraiy River section is divided into the Tigechan and Sebinekchan formations of the Lower Permian, and the Mugochan, Nyunegi, Mol, and Amkandzha formations of the Upper Permian. Fig. 2 illustrates correlation between two sections, one exposed at the left side of the Baraiy Canyon and

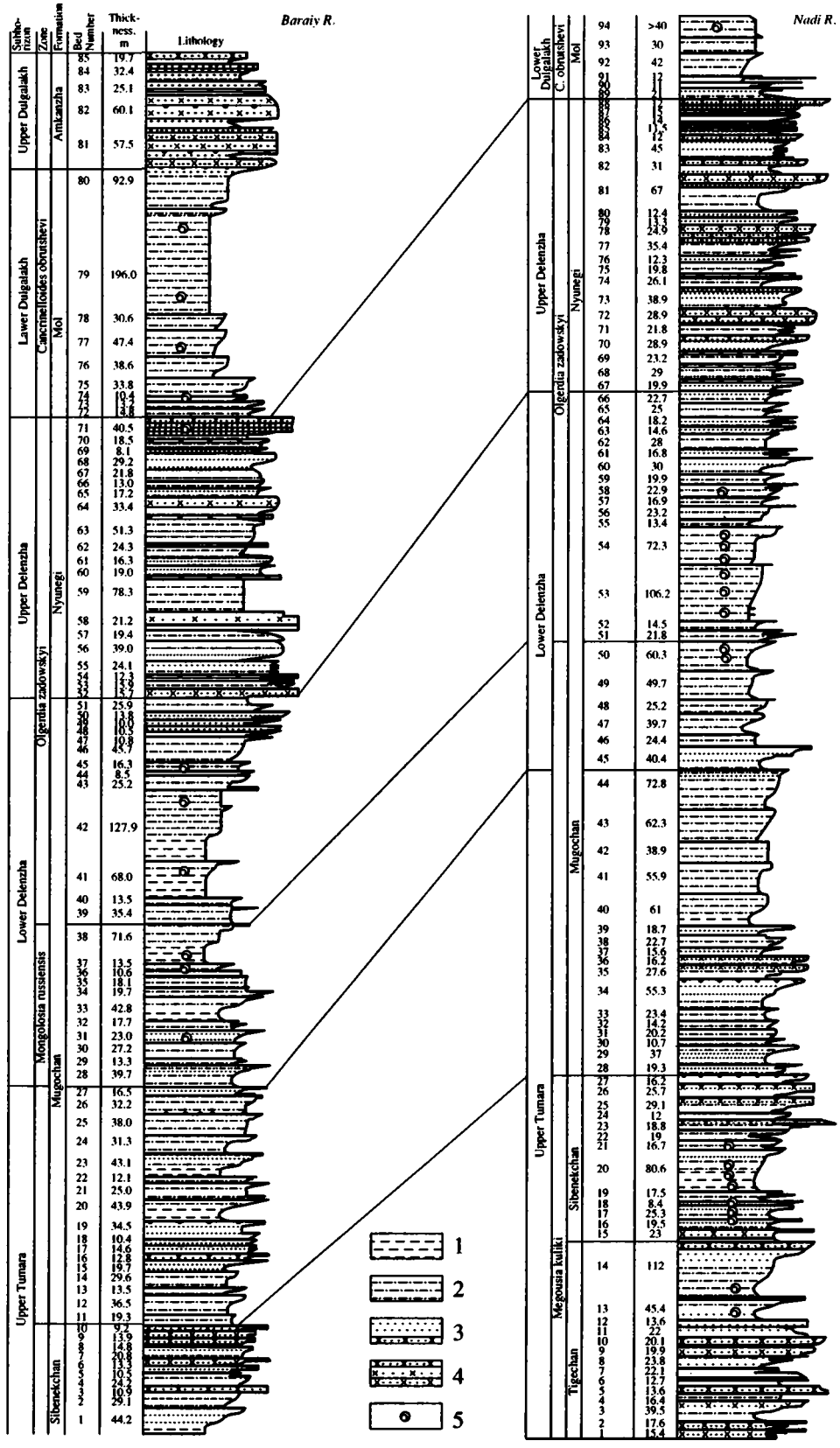


Fig. 2. The correlated Baraiy and Nadi river sections: (1) mudstone; (2) fine- to coarse-grained siltstone; (3) fine- to medium-grained sandstone; (4) coarse-grained sandstone; (5) occurrence levels of fossil discovered by authors.

Table 1. Correlation scheme for local and regional stratigraphic units

The Cisuralian region, stage	The Verkhoyansk region, subhorizon	The Endybal, Delenzha, and Tumara river basin, subformation	The Baraiy River basin, formation
Kazanian	Upper Delenzha	Upper Delenzha	Nyunegi
Ufimian	Lower Delenzha	Lower Delenzha	Mugochan
Kungurian	Upper Tumara	Upper Tumara	Sebinekchan
			Tigechan
	Lower Tumara	Lower Tumara	Talchan

another one near the Nadi River mouth (15 km downstream). Figure 3 shows the composite section, the lower part of which corresponds in lithologic and faunal characteristics to the Tigechan and Sebinekchan formations of the Nadi River section, and the upper one depicts the same characteristics of the Mugochan, Nyunegi, Mol, and Amkandzha formations of the Baraiy River section. Describing the distinguished biostratigraphic units we also used fossil identifications of other researchers.

Tumara Horizon, Upper Tumara Subhorizon

***Megousia kuliki* Zone.**[1] The zone spans the section interval from Bed 1 to Bed 14 (the Tigechan Formation), and further from Bed 15 to Bed 27 (the Sebinekchan Formation). The lower coarser deposits of the Tigechan Formation correspond to thick (5–15 to 20 m and thicker) members of medium- to fine-grained "blocky" sandstones characteristic of the topmost portions of the deltaic "wedges". The upper part of this formation represents a cyclic alternation of silty and sandy interbeds. According to Andrianov *et al.* (1975), this interval of the section corresponds to "flyschoid" stratotype of the rhythmic Tumara Formation and to the Takamkyt Formation of the Baraiy River basin. Siderite concretions in heavily bioturbated and fine-grained interbeds contain brachiopods and bivalves. The Tigechan Formation is about 375 m thick. It yielded brachiopod species *Alispiriferella gydanensis* (Zav.) and *"Neospirifer subfasciger"* Lich. characteristic of the Tumara Horizon (Solomina, 1997; Klets, 1995). The former was found together with the latest *Yakutoproductus* forms in the southeastern Verkhoyansk region (Klets, 1995). In the Kolyma–Omolon massif, the same species is confined to the *Mongolosia russiensis* Zone of the Omolon Horizon (Ganelin, 1990). This evident discrepancy has no explanation so far.

[1] Authors place lower boundaries of zonal units at the base of sedimentary rhythms, but not at the first occurrence levels of zonal assemblages that is not an apt decision. Reviewer A.S. Alekseev.

Andrianov reported on occurrence of *Anidanthus kolymaensis* (Lich.) (=*M. kuliki* (Fred.)), *Saccamina arctica* Gerke, and *Tumaroceras yakutorum* Ruzh. in the lower member of the upper Tumara Subformation (Andrianov, 1966, p. 45) and in the Takamkyt Formation (Andrianov *et al.*, 1975). These species are characteristic of the *M. kuliki* Zone.

The Sebinekchan Formation consists of alternating sandy and silty members in its upper and lower parts. Among them, there are 3- to 15-m-thick members of hard massive fine-grained and well-sorted calcareous sandstones of coastal-marine genesis, and of the deltaic medium- to fine-grained sandstones. These alternate with siltstone members having approximately the same thickness and frequently displaying structures of gravitational sliding. The deposits are heavily bioturbated. The middle part of the formation includes a thick (more than 80 m) member of predominantly silty sediments including interbeds of siderite fossiliferous concretions. Brachiopods are represented here by *Cancrinella janischewskiana* Step., *Megousia kuliki* (Fred.), *Rhynchopora* aff. *variabilis* Stuck., and *Tumarinia barajensis* Sol. Bivalve species are *Nuculana* cf. *undosa* Mur., *Aviculopecten mutabilis* Masl., *Streblopteria pusilla* (Schloth.), *Liebea squamosa* (Sowerby), *Praeundulomya petschorica* Mur. *Atomodesma andrianovi* Mur., *Aviculopecten orientalis* Fred., *Nuculana lunulata* (Demb.), *Vnigripecten* aff. *phosphaticus* (Girty), and *Parallelodon striatus* (Schlotheim).

Brachiopods *Megousia kuliki* (Fred.), *Tumarinia barajensis* Sol. and some bivalves (e.g., *Atomodesma andrianovi* Mur.) unambiguously evidence that their host deposits belong to the Tumara Horizon. Both brachiopods are index-species of the *Megousia kolymaensis* Zone in the schemes of Ganelin (1984, 1990) and Solomina (1997). Following Ganelin (1990), we consider the species *M. kolymaensis* (Lich.) as junior synonym of *M. kuliki* (Fred.). Solomina and Abramov differently dated the Sebinekchan (the upper part of the Sinigichan Formation according to Abramov, 1974) and overlying Mugochan formations. This could be

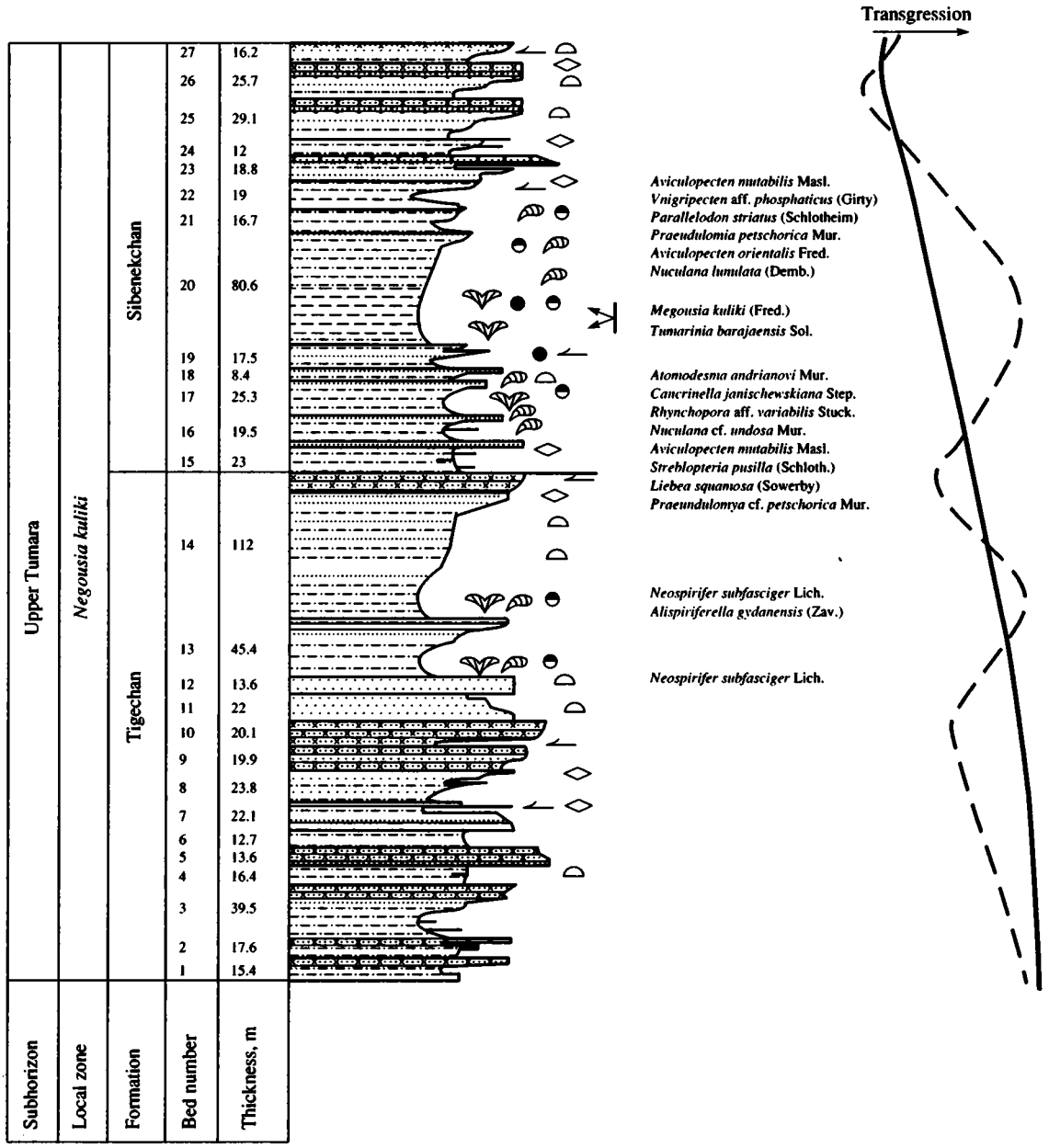


Fig. 3. The composite Baraiy section of the Lower–Upper Permian boundary deposits: (1) mudstone; (2) fine- to coarse-grained siltstone; (3) fine- to medium-grained sandstone; (4) coarse-grained sandstone; (5) ammonoids; (6) brachiopods; (7) bivalves; (8) foraminifers; (9) mud-eaters; (10) plant detritus; (11) floral remains; (12) sideritization; (13) pyritization; (14) oscillation ripple.

caused by find of *T. barajensis* Sol. in the Mugochan and Nyunegi formations (Abramov, 1974; Abramov and Grigor'eva, 1988), because this form was previously considered as index-species of the synonymous zone of the Tumara Horizon (Solomina, 1988). The find could allow Abramov to correlate the Mugochan Formation with the Tumara Formation of the Tumara River basin (the stratotype area of the Tumara Horizon), and this respectively influenced his interregional correlation.

The upper member of the upper Tumara Subformation of the Baraiy River basin yielded *Anidanthus kolymaensis* (Lich.) [=*M. kuliki* (Fred.)], *Tumaroceras yakutorum* Ruzh., *Cancrinella koninkiana* (Keys.), and others. The last indicated species is widespread in the Kungurian deposits of the North Urals and in the *M. kuliki* Zone of the Kolyma–Omolon massif.

***Kolymaella ogonerensis* Zone** characterizes Beds 28–44 (the Mugochan Formation) corresponding to two sedimentological rhythms of the section. It seems expedient to relate this unit with the next stage of the basin evolution. In his monograph on the Upper Paleozoic deposits of the western Verkhoyansk region,

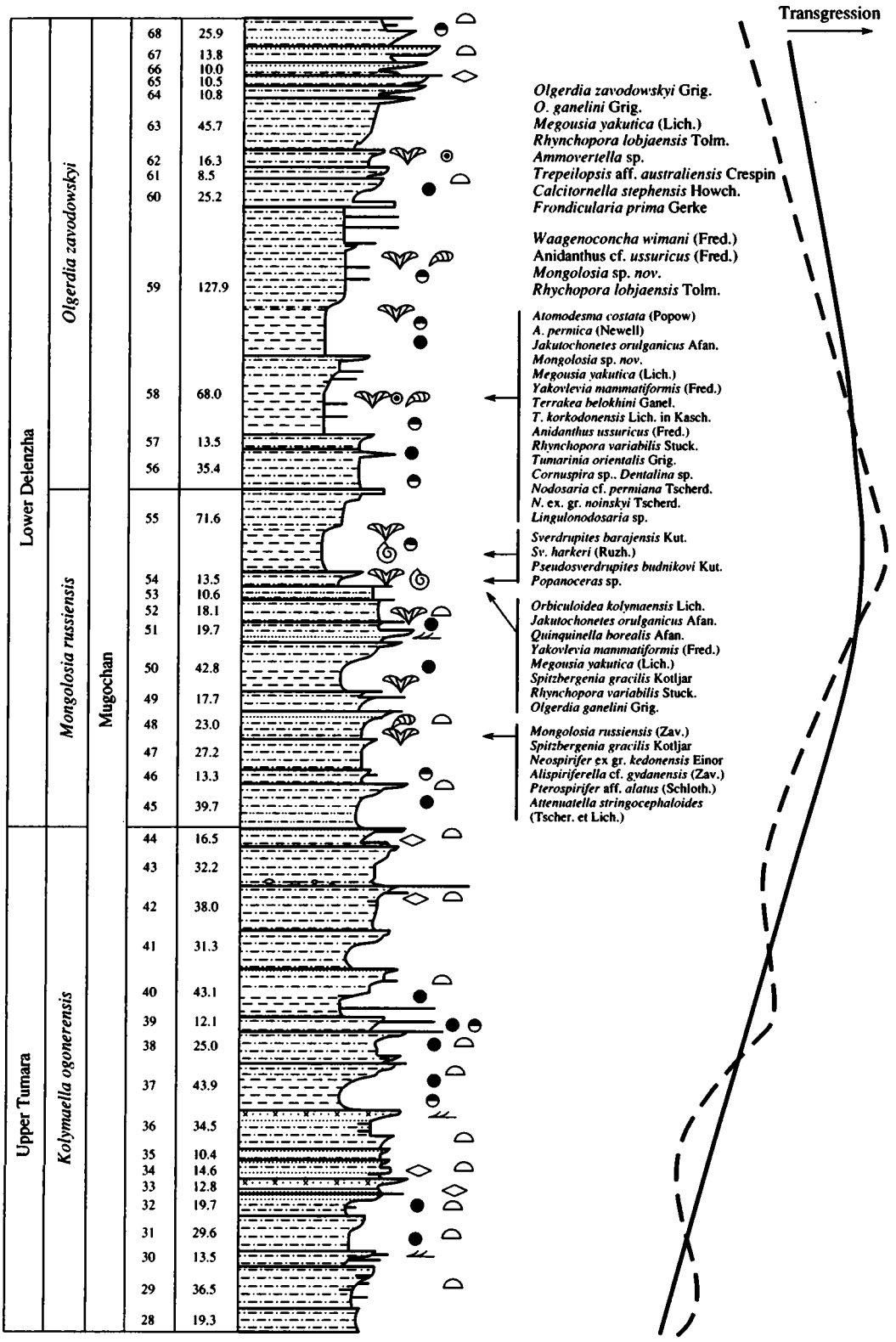
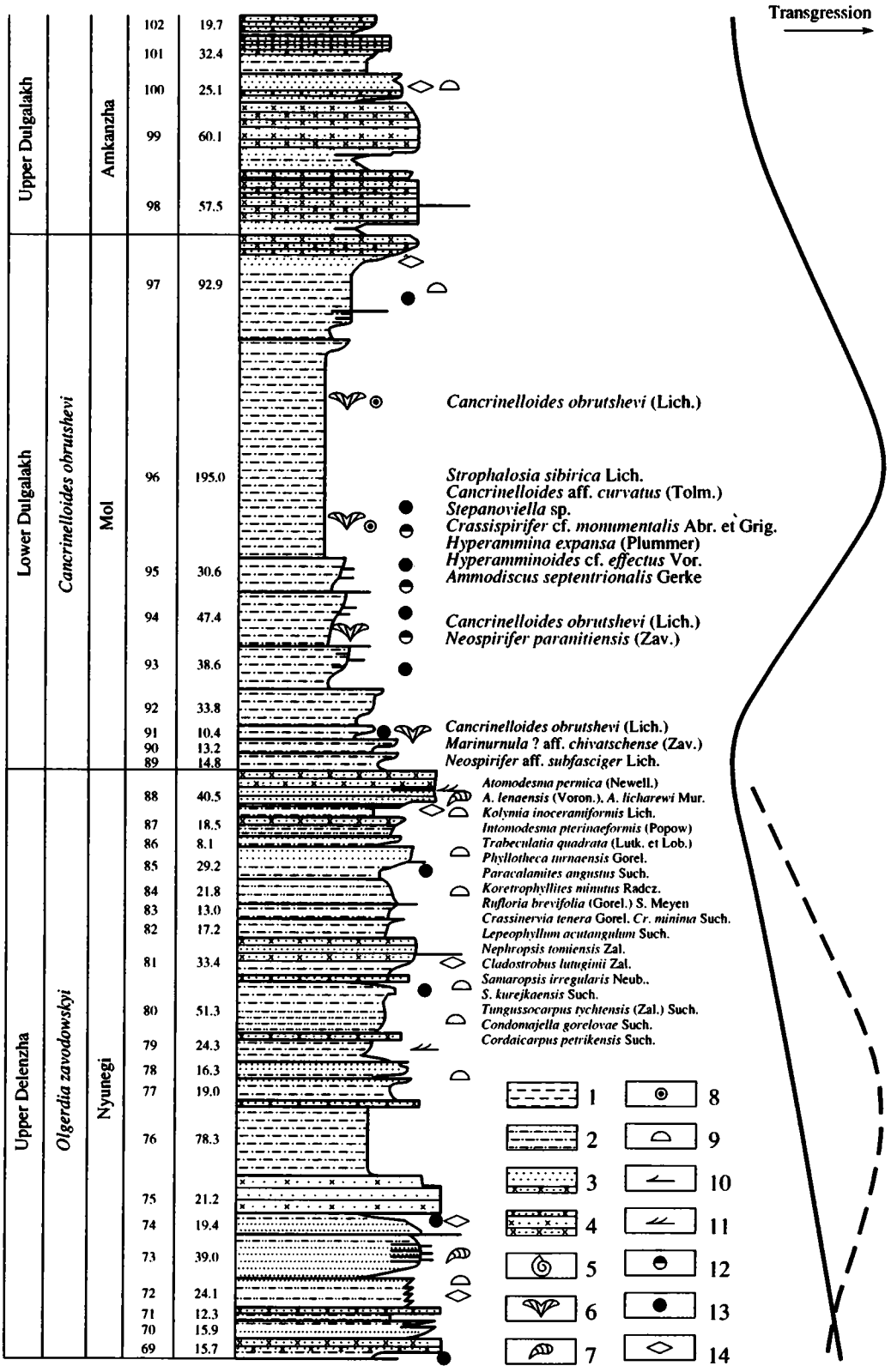

Transgression
Lower Delenzha
Upper Tumara
Olgerdia zavodowskyi
Mongolosia russiensis
Kolymaella ogonerensis
Mugochan
68 25.9
67 13.8
66 10.0
65 10.5
64 10.8
63 45.7
62 16.3
61 8.5
60 25.2
59 127.9
58 68.0
57 13.5
56 35.4
55 71.6
54 13.5
53 10.6
52 18.1
51 19.7
50 42.8
49 17.7
48 23.0
47 27.2
46 13.3
45 39.7
44 16.5
43 32.2
42 38.0
41 31.3
40 43.1
39 12.1
38 25.0
37 43.9
36 34.5
35 10.4
34 14.6
33 12.8
32 19.7
31 29.6
30 13.5
29 36.5
28 19.3
Olgerdia zavodowskyi Grig.
O. ganelini Grig.
Megousia yakutica (Lich.)
Rhynchopora lobjaensis Tolm.
Ammovertella sp.
Trepeilopsis aff. australiensis Crespin
Calcitornella stephensis Howch.
Frondicularia prima Gerke
Waagenoconcha wimani (Fred.)
Anidanthus cf. ussuricus (Fred.)
Mongolosia sp. nov.
Rhychopora lobjaensis Tolm.
Atomodesma costata (Popow)
A. permica (Newell)
Jakutochonetes orulganicus Afan.
Mongolosia sp. nov.
Megousia yakutica (Lich.)
Yakovlevia mammatiformis (Fred.)
Terrakea belokhini Ganel.
T. korkodonensis Lich. in Kasch.
Anidanthus ussuricus (Fred.)
Rhynchopora variabilis Stuck.
Tumarinia orientalis Grig.
Cornuspira sp., Dentalina sp.
Nodosaria cf. permiana Tscherd.
N. ex. gr. noinskyi Tscherd.
Lingulonodosaria sp.
Sverdrupites barajensis Kut.
Sv. harkeri (Ruzh.)
Pseudosverdrupites budnikovi Kut.
Popanoceras sp.
Orbiculoidea kolymaensis Lich.
Jakutochonetes orulganicus Afan.
Quinquinella borealis Afan.
Yakovlevia mammatiformis (Fred.)
Megousia yakutica (Lich.)
Spitzbergenia gracilis Kotljar
Rhynchopora variabilis Stuck.
Olgerdia ganelini Grig.
Mongolosia russiensis (Zav.)
Spitzbergenia gracilis Kotljar
Neospirifer ex gr. kedonensis Einor
Alispiriferella cf. gydanensis (Zav.)
Pterospirifer aff. alatus (Schloth.)
Attenuatella stringocephaloides
(Tscher. et Lich.)

Fig. 3. (Contd.)


Transgression
Upper Dulgalakh
Lower Dulgalakh
Upper Delenzha
Cancrinelloides obrutshevi
Olgerdia zavodowskyi
Amkanzha
Mol
Nyunegi
102 19.7
101 32.4
100 25.1
99 60.1
98 57.5
97 92.9
96 195.0
95 30.6
94 47.4
93 38.6
92 33.8
91 10.4
90 13.2
89 14.8
88 40.5
87 18.5
86 8.1
85 29.2
84 21.8
83 13.0
82 17.2
81 33.4
80 51.3
79 24.3
78 16.3
77 19.0
76 78.3
75 21.2
74 19.4
73 39.0
72 24.1
71 12.3
70 15.9
69 15.7
Cancrinelloides obrutshevi (Lich.)
Strophalosia sibirica Lich.
Cancrinelloides aff. curvatus (Tolm.)
Stepanoviella sp.
Crassispirifer cf. monumentalis Abr. et Grig.
Hyperammina expansa (Plummer)
Hyperamminoides cf. effectus Vor.
Ammodiscus septentrionalis Gerke
Cancrinelloides obrutshevi (Lich.)
Neospirifer paranitiensis (Zav.)
Cancrinelloides obrutshevi (Lich.)
Marinurnula ? aff. chivatschense (Zav.)
Neospirifer aff. subfasciger Lich.
Atomodesma permica (Newell.)
A. lenaensis (Voron.), A. licharewi Mur.
Kolymia inoceramiformis Lich.
Intomodesma pterinaeformis (Popow)
Trabeculatia quadrata (Lutk. et Lob.)
Phyllotheca turnaensis Gorel.
Paracalamites angustus Such.
Koretrophyllites minutus Radcz.
Rufloria brevifolia (Gorel.) S. Meyen
Crassinervia tenera Gorel. Cr. minima Such.
Lepeophyllum acutangulum Such.
Nephropsis tomiensis Zal.
Cladostrobus lutuginii Zal.
Samaropsis irregularis Neub.,
S. kurejkaensis Such.
Tungussocarpus tychtensis (Zal.) Such.
Condonajella gorelovae Such.
Cordaicarpus petrikensis Such.
1
2
3
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12
13
14

Fig. 3. (Contd.)

Andrianov (1966) referred these rhythms (submesocyclites) to the Tumara Formation, contrary to the logic of his own reconstructions. The members correspond to the initial phase of extensive transgression. In the facies zone under consideration, they compose the clayey–silty Mugochan Formation. In the Dulgalakh, Delenzha and Nuora river sections located westward, they are thinner and predominantly sandy. Consequently, the lower rhythm is usually included into the upper Tumara Subformation, and this is compatible with the natural structure of deltaic wedges extending from the Siberian platform. Ignoring this fact, we may come to erroneous stratigraphic reconstructions. Despite the thorough examination, no fauna was found in the described members, the constituent siltstones of which are heavily bioturbated.

Materials of geological mapping and data reported by Andrianov suggest that goniatites *Tumaroceras* aff. *yakutorum* Ruzh. (=*T. kashirzevi* Andr.), and *Tumaroceras* (?) sp. found at the Nadi River locality (Andrianov, 1985, p. 58) occur in the interval of Beds 28–44 (Fig. 3). *Baraioceras stepanovi* Andr. similar to the Kungurian *Paragastrioceras kungurense* (Mirskaya) was found by Andrianov and Shtekh (Andrianov, 1985, p. 58) in the Creek Imtan'ya alluvium (the area of distribution of the Tumara deposits); it may also characterize this interval. Solomina (1997) reported on occurrence of the brachiopod zonal species *ogonerensis* in the same interval of the Baraiy River section, where she recognized the synonymous zone.

Delenzha Horizon

The horizon consists of two subhorizons. The lower Delenzha Subhorizon spans the *Mongolosia russiensis* and *Olgerdia zavodovskyi* zones and corresponds to the upper part of the Mugochan Formation (Beds 45–68, Fig. 3). The formation composed of predominantly silty deposits displaying cyclic structure was accumulated during the early Delenzha stage of an intense transgression. The formation is subdivided into several members. Upper siltstone layers of the members are coarser than in their lower parts and include sandstone interbeds, especially closer to the formation base. These are the so-called submesocyclites readily traceable over the western Verkhoyansk region.

***Mongolosia russiensis* Zone.** The zone corresponds to the interval of Beds 45–55 (Fig. 3) and yields ammonoids *Sverdrupites baraiensis* Kut., *Sv. harkeri* (Ruzh.), *Sv.* aff. *harkeri* (Ruzh.), *Pseudosverdrupites budnikovi* Kut., and *Popanoceras* sp. indet. In association with brachiopods *Orbiculoidea kolymaensis* Lich., *Jakutochonetes orulganicus* Afan., *Quinquinella borealis* Afan., *Mongolosia russiensis* (Zav.), *Yakovlevia mammatiformis* (Fred.), *Megousia yakutica* (Lich.), *Spitzbergenia gracilis* Kotljar, *Rhynchopora variabilis* Stuck, *Olgerdia ganelini* Grig., *Neospirifer* ex gr. *kedonensis* Einor, *Alispiriferella* cf. *gydanensis* (Zav.), *Pterospirifer* aff. *alatus* (Schloth.), and *Attenuatella stringocephaloides* (Tschern. et Lich.). In the lower Delenzha Subformation of the Baraiy River section, Andrianov found *Popanoceras subtumarense* Andr. and *Daubichites* aff. *goochi* (Teichert).

The ammonoids unambiguously indicate the Roadian age of their host deposits (Andrianov, 1985; Kutygin, 1996, 1997). Brachiopods are characteristic in general of the basal Upper Permian deposits in many areas of northeastern Russia. According to Solomina (1997), the Mugochan Horizon contains *Jakutochonetes orulganicus* Afan., *Megousia yakutica* (Lich.), and *Mongolosia russiensis* (Zav.). The Omolon Horizon includes *Megousia yakutica* (Lich.), *Spitzbergenia gracilis* Kotljar, *Mongolosia russiensis* (Zav.), *Attenuatella stringocephaloides* (Tschern. et Lich.), and others (Ganelin, 1990). *Yakovlevia mammatiformis* (Fred.) is a characteristic form of the *Anidanthus aagardi* Zone of the Kolyma–Omolon massif (the Dzhigdala Horizon, Ganelin, 1990) and of the Talata Formation of the Pai-Khoi area (the Kungurian Stage, Kalashnikov, 1993). The same zonal species is also known from the Vladivostok Horizon of the Primor'e (Kotlyar, 1997). The brachiopod assemblage is commonly considered to be of the Ufimian age.

***Olgerdia zavodowskyi* Zone** was originally established and described by Solomina (1986, 1997). It corresponds to the interval of Beds 56–68 (the Mugochan Formation) and 69–88 (the Nyunegi Formation) of the section. The corresponding brachiopod assemblage includes *Jakutochonetes orulganicus* Afan., *Mongolosia* sp. nov., *Yakovlevia mammatiformis* (Fred.), *Megousia yakutica* (Lich.), *Waagenoconcha wimani* (Fred.), *Anidanthus* cf. *ussuricus* (Fred.), *Terrakea belochini* Gan., *T. korkodonensis* (Lich.), *Rhynchopora variabilis* Stuck., *Rhynchopora lobjaensis* Tolm., *Tumarinia orientalis* Grig., *Olgerdia zavodovskyi* Grig., and *O. ganelini* Grig. Coexisting foraminifers are represented by *Cornuspira* sp., *Nodosaria* cf. *permiana* Tscherd., *N.* ex gr. *noinskyi* Tscherd., *Dentalina* sp., *Lingulonodosaria* sp., *Ammovertella* sp., *Trepeilopsis* aff. *australiensis* Crespin, *Calcitornella stephensis* Howch., *Frondicularia prima* Gerke, and *Glomospira* ex gr. *gordialis* Par. et Jan.

Brachiopods *Terrakea belochini* Gan., *T. korkodonensis* (Lich.), *Megousia yakutica* (Lich.), and *Tumarinia orientalis* Grig. are characteristic forms of the *Terrakea korkodonensis* Zone of the Kolyma–Omolon massif (Ganelin, 1990). *Olgerdia zavodovskyi* Grig. and *O. ganelini* Grig. characterize upper beds of the Omolon Horizon of that massif (Ganelin, 1990; Abramov and Grigor'eva, 1988) and the Nyunegi Horizon (Solomina, 1997). *Waagenoconcha wimani* (Fred.) is reported from the *Megousia kuliki* Zone (equivalent to the Kungurian deposits) of the Kolyma–Omolon massif (Ganelin, 1990). This species and *Anidanthus ussuricus* (Fred.) are included in the list of fossils from the *Timorites* Beds of the Midian Stage (Kotlyar *et al.*, 1997), which correspond to the *Cancrinelloides curva-*

Table 2. Biostratigraphy of the Lower-Upper Permian boundary deposits in the western and northern Verkhoyansk areas

Uralian scale		Verkhoyansk regional scale			Correlation of sections			Adjacent region	
Stage	Horizon	Horizon	Subhorizon	Zone	Western Verkhoyansk area		Northern Verkhoyansk area	The Kolyma–Omolon massif (Ganelin, 1984, 1990)	
					The Baraiy Zone	The Eastern Kuranakh Zone	The Eastern Kharaulakh Zone		
					The Baraiy R.	The Delenzha and Tumara R.			
Tatarian	Urzhum	Dulgalakh	Lower Dulgalakh	*Cancrinelloides obrutshevi*	Mol Fm.	Lower Dulgalakh Subfm.	Upper Chabardak Subfm.	*Cancrinelloides obrutshevi*	
Kazanian		Delenzha	Upper Delenzha	*Olgerdia zavodovskyi*	Nyunegi Fm.	Upper Delenzha Subfm.	Lower Chabardak Subfm.	*Magadania bajkurica*	
							Boguchan Fm.		
			Lower Delenzha		Mugochan Fm.	Lower Delenzha Subfm.	Makhchar Fm.	*Ter. korkodonensis-Omolonia snjatkovi*	
Ufimian	Sheshma			*Mongolosia russiensis Daubichites-Sverdrupites harkeri*				*Mongolosia russiensis*	
	Solikamsk	Tumara	Upper Tumara	*Kolymaella ogonerensis Tumaroceras kashirzevi*		Upper Tumara Subfm.	Meichan Fm.	Dzhigdala Horizon	*Kolymaella ogonerensis*
Kungurian	Iren'			*Megousia kuliki-Neouddenites-Tumaroceras yakutorum*	Sebinekchan Fm.		Khaldzha Fm. (upper part)		*Megousia kuliki*
	Fillipovka				Tigechan Fm.				

tus Beds of boreal regions. According to the general composition of the brachiopod assemblage, the deposits in question can be attributed to stratigraphic analogues of the Ufimian Stage (e.g., to the Lower Delenzha Subhorizon).

The lower boundary of the Nyunegi Formation is drawn at the base of the lowest thick sandstone interbed. The formation is predominantly composed of coastal-marine sandstone members, which are 3 to 20 m thick and reveal ripple marks. The intercalated siltstone interbeds of approximately the same thickness represents elementary cyclites of regressive phases. The deposits are heavily bioturbated and frequently show structures of gravitational sliding. The formation is 532 m thick.

The bivalve assemblage consists of *Atomodesma permica* (Newell.), *A. lenaensis* (Voron.), *A. licharewi* Mur., *Kolymia inoceramiformis* Lich., *Trabeculatia* cf. *quadrata* (Lutk. et Lob.), and *Intomodesma* cf. *pterinaeformis* (Popow). These species characterize the Dzhigdala–Omolon phase of bivalve evolution, whereas *T. quadrata* (Lutk. et Lob.) and *I. pterinaeformis* (Popow) are peculiar of the second half of that phase (Astaf'eva, 1998).

A clay interbed of the upper part of the formation (avandelta facies) yielded floral remains, such as *Phyllotheca turnaensis* Gorel., *Paracalamites angustus* Such., *Koretrophyllites minutus* Radcz., *Rufloria brevifolia* (Gorel.) S. Meyen, *Crassinervia tenera* Gorel., *Cr. minima* Such., *Lepeophyllum acutangulum* Such., *Nephropsis tomiensis* Zal., *Cladostrobus lutuginii* Zal., *Samaropsis irregularis* Neub., and *S. kurejkaensis* Such. According to Gorelova, this flora is typical of the Kuznetsk time in the synonymous coalfield.

We found no brachiopods in the formation. Solomina (see in Abramov *et al.*, 1973) discovered *Cancrinelloides obrutshevi* (Lich.) that was reclassified afterward into *Cancrinelloides juregensis* Sol. (Solomina, 1997) found 100 m below the top of the formation stratotype. *Rhynchopora lobjaensis* Tolm. and abundant *Licharewia* cf. *stuckenbergi* (Netsch.) were encountered at the level of 100 m above the base of the Nyunegi Formation parastratotype (Abramov *et al.*, 1973). In her scheme, Solomina (1997) most likely indicated the last species as *Olgerdia zavodovskyi* (Gan.) and *Strophalosia sibirica* Lich. as *Strophalosia tolli* (Fred.). Abramov and Grigor'eva (1988) detected *Rhynchopora lobjaensis* Tolm. and *Tumarinia barajensis* Sol. in the lowermost beds of the formation. In their opinion, the latter also occurs in the middle part of the underlying Mugochan Formation. We deliberately cite all the brachiopod occurrences in the Mugochan and Nyunegi stratotypes and parastratotypes, as they are reported by Solomina (1997) and also by Abramov and Grigor'eva (1988) despite the essentially different conclusions the authors arrived at. In both works, the Mugochan and Nyunegi formations are attributed to the Omolon Horizon of the Kolyma–Omolon massif, but the suggested correlation of regional horizons in the stratotype area differs substantially, as is noted above.

Dulgalakh Horizon, Lower Dulgalakh Subhorizon

***Cancrinelloides obrutshevi* Zone.** corresponds to Beds 89–97 of the section (the Mol Formation). The formation is composed of inequigranular siltstones forming elementary cyclites (rhythms) of regressive type (Fig. 3). Its lower boundary is drawn at the top of the thick interbed of blocky sandstones. The fine-grained siltstones and mudstones in the upper part of the formation contain angular fragments of clayey limestone, the so-called "ryabchiki" (Grinenko *et al.*, 1997). The formation yielded brachiopods *Cancrinelloides obrutshevi* (Lich.), *C.* aff. *curvatus* (Tolm.), *Stepanoviella* sp., *Strophalosia sibirica* Lich., *Marinurnula* ? aff. *chivatschense* (Zav.), *Crassispirifer* cf. *monumentalis* Abr. et Grig., *Neospirifer paranitiensis* (Zav.), and *N.* aff. *subfasciger* Lich. In association with foraminifers *Hyperammina expansa* (Plummer), *Hyperamminoides* cf. *effectus* Vor., and *Ammodiscus septentrionalis* Gerke. These fossils suggest that their host deposits are coeval to the lower half of the Gizhiga Horizon (the *C. obrutshevi* Zone; Ganelin, 1984, 1990). The synonymous zone of the same scope is included in the scheme of Solomina (1997). Genesis of these deposits widespread in northeastern Russia was a subject of long discussion. We support the opinion that the avalanche sedimentation played a significant role in this case (Grinenko *et al.*, 1997). The viewpoint of Kolyasnikov (1997) who argued for influence of seismic sea waves (tsunami) on sedimentation seems interesting as well. We accept the general opinion on the early Tatarian age of the considered zone (Table 2).

EVENTS

The analysis of cyclic sedimentation and changes in fauna composition at the beginning of different sedimentary cycles allow us to distinguish a series of biotic and abiotic events of different correlation value, which took place during the late Early–early Late Permian in the Verkhoyansk region. The biostratigraphic zones correspond to different phases of the transgressive–regressive cycles. The distinguished events are of the short- and long-term types. The former characterize episodes of replacement of one faunal assemblage by another, changeover time of sedimentation regime, and commencement of particular transgressive–regressive cycles. The long-term events correspond to existence periods of zonal assemblages and to phases of the highest sea level stand. We recognize the following succession of the early to later events:

(1) The *Megousia kuliki* phase that coincides with the low-order transgressive–regressive cycle against the background regression of the Late Tumara sea; the phase was long, and its beginning and termination remain obscure.

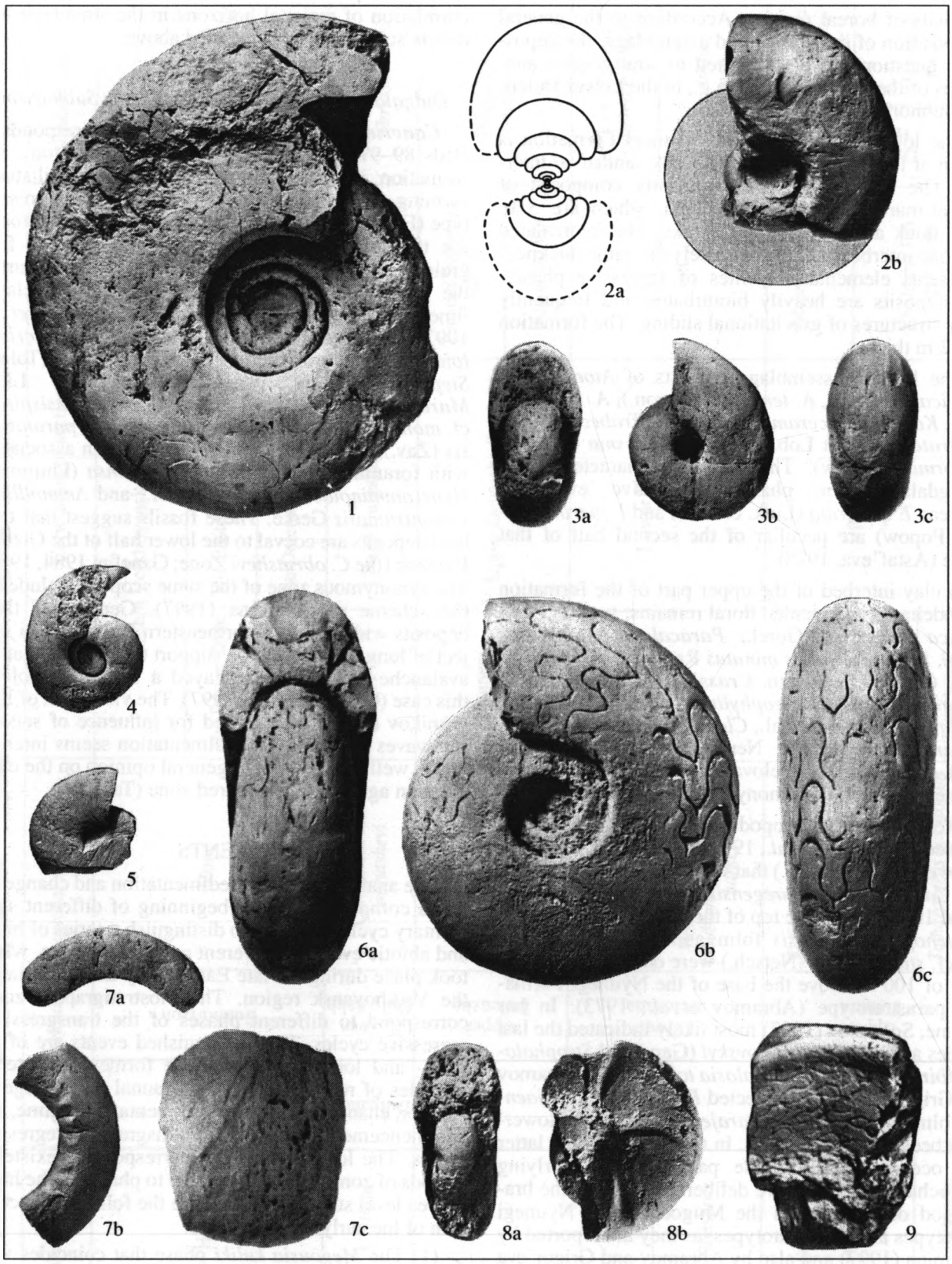
1
2a
2b
3a
3b
3c
4
5
6a
6b
6c
7a
7b
7c
8a
8b
9

Plate I. Ammonoids.

(1) *Daubichites goochi* (Teichert); specimen no. 55/261, ×0.4; upper reaches of the Baraiy River (the left slope, 1.5–1.8 km upstream the Creek Imtan'ya mouth); the lower part of the Lower Delenzha Subformation; collection of Andrianov, sample 11-1966.

(2, 4) *Pseudosverdrupites budnikovi* Kutygin: (2) holotype no. 16/173, (4) specimen no. 13/173, ×1.2; the upper reaches of the Baraiy River, the Creek Ammonitovyi, 420 m upstream the mouth (right side); Mugochan Formation (Bed 54 in Fig. 3); collection of Budnikov and others, samples 1 and 82(92)-61-1992.

(3, 6) *Sverdrupites harkeri* (Ruzhencev): (3) specimen 5/173; upper reaches of the Baraiy River, the Creek Ammonitovyi, 420 m upstream of the mouth (right side); Mugochan Formation (Bed 54 in Fig. 3); collection of Budnikov and others, sample 1i/82(92)-61-1992, (6) specimen 55/262, ×0.5; upper reaches of the Baraiy River (left slope, 1.5–1.8 km upstream of the Creek Imtan'ya); the lower part of the Lower Delenzha Subformation; collection of Andrianov, sample 11-1966.

(5) *Sverdrupites baraiensis* Kutygin; holotype no. 23/173; upper reaches of the Baraiy River, the Creek Ammonitovyi, about 1 km upstream the mouth (left side); Mugochan Formation (Bed 55 in Fig. 3); collections of Kutygin, sample 5/1-1992.

(7) *Baraioceras stepanovi* Andrianov; holotype no. 55/29, ×0.55; upper reaches of the Baraiy River, the Imtan'ya River (lower course); alluvium in the area of the Tumara Formation, upper subformation; collection of Andrianov and Shtekh, sample 506/11a-1963.

(8) *Popanoceras subtumarense* Andrianov; holotype no. 55/574, ×2.3; upper reaches of the Baraiy River (the Creek Bezymyannyi mouth), the lower part of the Lower Delenzha Subformation; collections of Andrianov and others, sample 506-1972.

(9) *Neouddenites andrianovi* Ruzhencev; specimen no. 55/25; upper reaches of the Baraiy River, the left tributary upstream the Kommunar Settlement; Echa Formation; collection of Andrianov and others, sample 504/1-1963, Early Permian, Artinskian–Kungurian.

(2) The beginning of the Mugochan sea transgression; the event was distinct, though recorded not everywhere because of local peculiarities. The aforementioned problem of transitional beds between the Tumara and Delenzha formations is related.

(3) The *Kolymaella ogonerensis* phase that marks the beginning of the next transgression; the corresponding transgressive–regressive cycle includes three phases: the beginning of transgression, the period of highest sea level stand, and regression phase. The faunal assemblage is closely interrelated with the previous one, but signifies the commencement of a new cycle.

(4) The first occurrence of brachiopods of the *Mongolosia russiensis* Zone and Roadian ammonoid assemblage.

(5) The *Mongolosia russiensis* phase that coincides with the phase of the highest sea level stand; sediments of the phase contain abundant marine fossils (the Roadian ammonoids included) thus being of the highest correlation potential (Kutygin, 1996; Kotlyar, 1997; Nassichuk, 1995).

(6) The *Cancrinelloides obrutshevi* phase; like the previous one, it coincides with the highest sea level stand during the subsequent transgressive-regressive cycle of the highest order.

Plate II. Brachiopods

(1, 2) *Tumarinia barajensis* Sol.: (1) ventral valve, ×1, the Nadi River; Sibenekchan Formation, Bed 20 in Fig. 3 (sample 2i/92-39, 1612 m), (2) ventral valve, view from the area, ×1, the Nadi River; Sibenekchan Formation, Bed 20 in Fig. 3 (Sample 2i/92-39, 1660 m); herein and after: collections of Budnikov and others, 1992–1993.

(3) *Alispiriferella gydanensis* (Zav.); ventral valve, ×1.2, the Nadi River; Tigechan Formation, Bed 14 in Fig. 3 (Sample 2i/92-39, 1312 m).

(4) *Megousia yakutica* (Lich.); cast of the ventral valve, ×1, the Baraiy River; Mugochan Formation, Bed 58 in Fig. 3 (Sample 1i/92-56, 2352 m).

(5, 6) *Megousia kuliki* (Fred.): (5) ventral valve, ×1.25, the Nadi River; Sibenekchan Formation, Bed 20 in Fig. 3 (Sample 2i/92-39, 1612 m); (6) ventral valve, ×1, the Nadi River; Sibenekchan Formation, Bed 20 in Fig. 3 (Sample 2i/92-39, 1612 m).

(7) *Olgerdia zavodovskyi* Grig.: the shell cast, ×1, ventral view (7a) and dorsal view (7b); the Baraiy River; Mugochan Formation, Bed 62 in Fig. 3 (Sample 1i/92-51, 2104 m).

(8) *Mongolosia russiensis* (Zav.); interior of the dorsal valve, ×1; the Baraiy River; Mugochan Formation, Bed 48 in Fig. 3 (Sample 1i/92-70, 2661 m).

(9) *Yakovlevia mammatiformis* (Fred.); cast of the ventral valve, ×1; the Baraiy River; Mugochan Formation, Bed 58 in Fig. 3 (Sample 1i/92-56, 2352 m).

(10, 11) *Terrakea korkodonensis* (Lich. in Kasch.): (10) imprint of the dorsal valve, ×1, (11) imprint of the ventral valve, ×1; the Baraiy River; Mugochan Formation, Bed 58 in Fig. 3 (Sample 1i/92-56, 2352 m).

(12) *Terrakea* cf. *belokhini* Gan.; cast of the ventral valve, ×1; the Baraiy River; Mugochan Formation, Bed 58 in Fig. 3 (Sample 1i/92-56, 2352 m).

(13, 14) *Pterospirifer* aff. *alatus* (Schloth.); casts of the ventral valves, ×1; the Baraiy River, Mugochan Formation, Bed 48 in Fig. 3 (Sample 1i/92-70, 2661 m).

(15) *Spitzbergenia gracilis* Kotljar; shell, ×1; the Baraiy River; Mugochan Formation, Bed 48 in Fig. 3 (Sample 1i/92-70, 2661 m).

(16, 17) *Cancrinelloides obrutshevi* (Lich.): shell cast, view from the ventral valve, ×1.4 (16a) and from the dorsal valve, ×1 (16b); the Baraiy River, Mol Formation, Bed 91 in Fig. 3 (Sample 1i/92-15, 1060 m); (17) ventral valve, ×1; the Baraiy River, Mol Formation, Bed 96 in Fig. 3 (Sample 1i/92-10, 540 m).

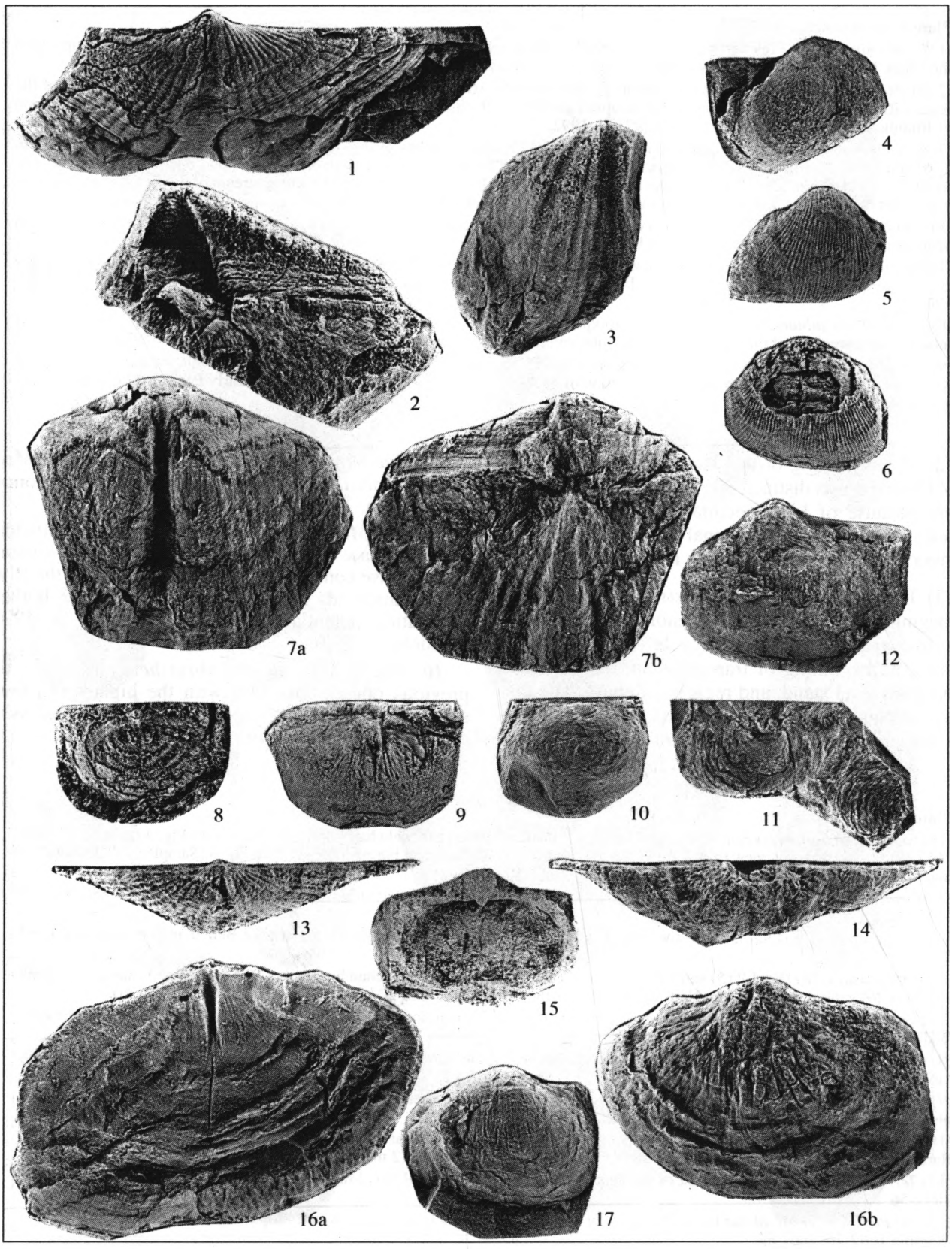
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Table 3. Correlation of stratigraphic subdivisions of the western Verkhoyansk region with those accepted in Russia and suggested by the International Commission on Stratigraphy

Stage	Ubhorizon	Zone	Series
Ufimian	Lower Delenzha	*Mongolosia russiensis*	Guadalupian
	Upper Tumara	*Spitsbergenia ogonerensis*	Cisuralian
Kungurian		*Megousia kuliki*	

CONCLUSIONS

The analysis of geological records outlining the short- and long-term biotic and abiotic events lead to definite conclusions. The most significant short-time event is marked by appearance of brachiopods of the *M. russiensis* Zone and coeval ammonoid assemblage (point 4 above). The event is correlative with the early Roadian of the North American scale and with the boundary between the Solikamsk and Sheshma horizons of the Uralian scale.

According to resolutions of the Interdepartmental Stratigraphic Committee and Conference on Regional Stratigraphy (*Resheniya...*, 1982), the Lower–Upper Permian boundary is drawn at the base of the Solikamsk Horizon, or inside the Tumara Horizon (point no. 2 above) at the last occurrence level of the *Megousia kuliki* zonal assemblage, or at the base of the *Kolymaella ogonerensis* Zone that yields the *Tumaroceras kashirzevi* Andr. ammonoid assemblage.

Thus, we distinguished the following faunal succession in the Lower–Upper Permian boundary deposits of the Baraiy River section: *Megousia kuliki–Kolymaella ogonerensis–Mongolosia russiensis* (Table 3). The first species is associated with goniatite *Tumaroceras yakutorum* and brachiopods of the *Cancrinella coninkiana* group. The second species coexisted with *Tumaroceras kashirzevi* Andr. and, probably, with *Baraioceras stepanovi*. The third one was found together with the *Sverdrupites harkeri* and *Daubichites* assemblages of Roadian ammonoid. Genera *Tumaroceras* and *Epijuresanites* previously considered as endemic were found recently in Kungurian deposits of the Urals, Pai-Khoi and other regions (Chuvashov, 1997; Bogoslovskaya, 1997; Kotlyar, 1997). These finds suggest that the Lower–Upper Permian boundary should be placed inside the upper Tumara Horizon at the level, where the brachiopod assemblage of the *Megousia kuliki* zone is replaced by that of the *Kolymaella ogonerensis* Zone. However, we should admit that the most significant biotic event is recorded in the western Verkhoyansk region at the base of the brachiopod *Mongolosia russiensis* Zone also bearing goniatites. This level corresponds to the boundary between the Cisuralian and Guadalupian series, or between the Kungurian (the Solikamsk Horizon inclusive) and Roadian stages.

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The Early Kazanian "Soyana River Flora": Its Place among Coeval Floras and in Phytogeographic Zones of the Angaraland

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Abstract—The early Kazanian flora of the Soyana River site includes the following plant groups: ruflorians *Rufloria sylovaensis* (Neub.) comb. Nov.; vojnovskyans *Cordaites* sp., *Crassinervia* sp., *Lepeophillum* sp., *Sylvella* sp., *Jordania* sp., *Samaropsis* spp., and *Cordaicarpus* sp.; conifers *Cyparissidium* sp.; dicranopylls *Entsovia* cf. *rarisulcata* S. Meyen; small-leaved *Zamiopteris* ex gr. *elongata* (Zal.) Neub.; cardiolepidians *Phylladoderma* sp.; pteridosperms *Cardioneura* ex gr. *vorcutense* Zal.; lepidophytes *Viatscheslaviophyllum* cf. *kamiense* Esaul.; ferns *Pecopteris* ex gr. *leptophylla* Bunb. and *Lobatopteris* sp.; articulates *Annularia* aff. *carinata* Gutb. Regional Kazanian floras and reconstructed phytogeographic zones of the Angaraland are considered. The extreme northern part of the Angaraland presumably corresponded to a narrow tundra zone with cold climate. The boreal zone with moderately cold, predominantly humid climate occupied the greater part of the land that was covered with forest massifs ("cordaitean taiga"). Southwestern areas of the Angaraland (cis-Urals and northern part of the Russian platform) represented the subboreal zone of moderately warm climate that hosted plant formations of several types, among them the deciduous cordaitean and cardiolepidian forests, which grew within present-day areas of the cis-Urals and Pechora basin. Westward of the Angaraland, the subboreal zone is traceable in the Arctic North America. The early Kazanian "Soyana River flora" presumably represented an island plant formation of the subboreal zone. Ferns and articulates occurring in this flora are characterized.

Key words: *Kazanian Stage, paleophytogeography, phytogeographic zones, Russian platform, flora, pteridophytes.*

INTRODUCTION

The Late Permian Soyana River flora was discovered by Zalessky (1937) almost half a century ago, but it was not studied in detail so far. Plant remains occur in a single site near the Iva-Gora Village of the Arkhangel'sk district, within the so-called Iva-Gora Beds or facies (Fig. 1, *1*).

The Iva-Gora Beds of the Soyana River basin were recognized by Zekkel (1939). The beds that are chiefly composed of gray marl and sandstone conformably rest on red beds of the Sheshma Horizon of the Ufimian Stage. The marly interlayers yield abundant plant remains and fossil insects. In the easterly direction, the sandstone and sandy marl facies grade into rocks of a more distinct marine genesis. The later are intercalated with limestone interlayers that yield the following invertebrates of the early Kazanian habit: *Nodosaria hexagona* Teherd., *Lingulonodosaria kamensis* K. V.-Maklay, *Spandelina longissima* K. M.-Maklay, *Tristix permiana* Gerke, *Lingula orientalis* Gol., *Rhynchopora geinitziana* Vern., *Astartella permocarbonica* Teherd., *Atula kutorgana* Vern. (Likharev and Miklukho-Maklay, 1977), and ammonoids *Pseudogastrioceras (?)* sp. (Kulikov *et al.*, 1973). Accordingly, their host deposits were attributed to the lower Kazanian Substage (Likharev and Miklukho-Maklay, 1977).

The early Kazanian plant remains studied in this work were collected at the Soyana River site in 1972 by paleoentomologist A.G. Sharov (Institute of Paleontology RAS, Moscow). The material is represented by weakly metamorphosed phytoleims that are appropriate for the standard maceration procedure in Schultze's solution. Plant fossils were investigated under the binocular microscope MBS-9. Studying microstructures of phytoleims, we used the scanning electron microscope Stereoscan 600. Illustrations are drawn after photographs with the help of cross-haired ocular. The material is stored at the Geological Institute RAS (collection no. 4547).

Characterizing and describing floral remains, we followed the higher plant systematics by Meyen (1987) except for the traditional term of paleobotany "pteridosperms." The latter is used here to designate an informal grouping that includes Gymnospermae orders Callistophytales, Gigantonomyales, Peltaspermales, Caytoniales, Lagenostomales, and Trigonocarpales, all listed by Meyen in his systematics.

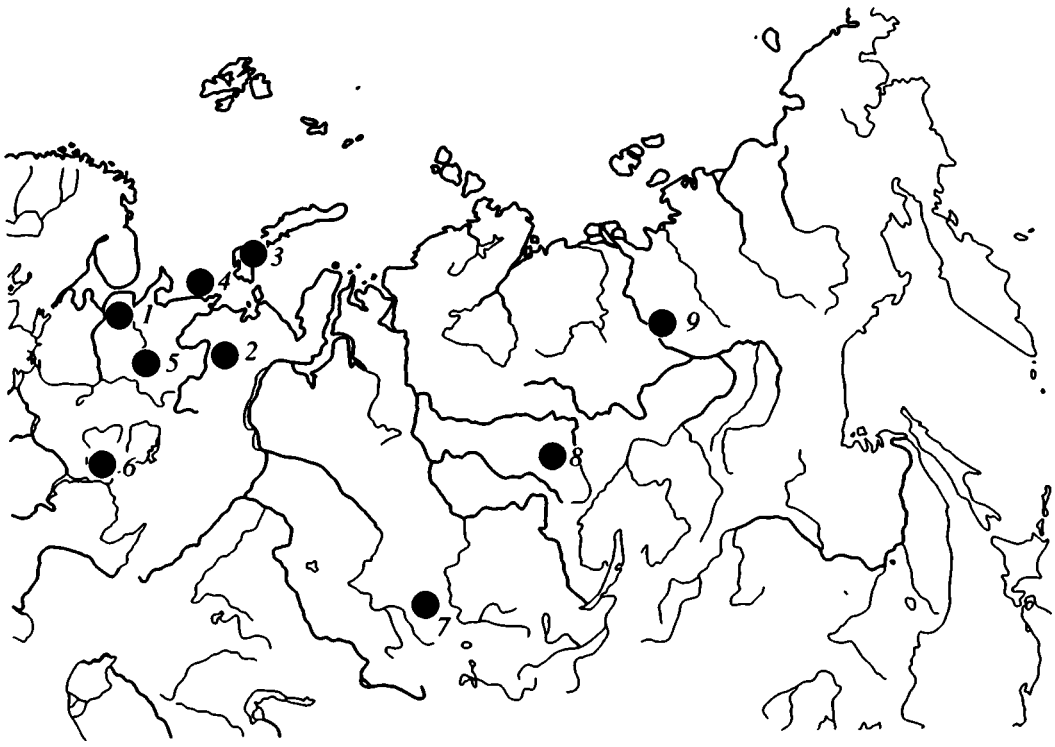

Fig. 1. Main Angaraland areas with known localities of Kazanian floras: (*1*) Soyana River (Iva-Gora site); (*2*) Pechora basin and adjacent area of the cis-Urals; (*3*) Novaya Zemlya Islands; (*4*) Kolguev Island; (*5*) western cis-Timan; (*6*) Volga–Urals region; (*7*) Kuznetsk basin; (*8*) Tunguska basin; (*9*) western Verkhoyansk area.

PLACE OF THE SOYANA RIVER FLORA AMONG KAZANIAN FLORAS OF THE ANGARALAND

Kazanian floras of the Angaraland are poorly studied. This statement means not only the inadequate taxonomic investigation and uncertainty in species determinations, but also the "taxonomic provincialism" responsible for the controversial regional nomenclature of morphologically identical forms found in different regions. For instance, paleobotanists who work in the Pechora basin and cis-Urals define the cordaitean leaves, in accordance with the regional tradition, as *Cordaites brevis* (Neub.) S. Meyen, whereas their colleagues who investigate the coeval flora in the central Angaraland identify the same leaf remains as *Cordaites gracilentus* (Gorel.) S. Meyen. Absolutely the same could be stated with respect to dispersal seed remains *Bardocarpus superus* Neub. and *Tungussocarpus tychtensis* (Zal.) Such., the former widespread in the Pechora basin and cis-Urals, and the latter occurring in coeval deposits of the central Angaraland.

There is also an opposite tendency to universalize taxa for morphologically similar forms despite the fact that they are found in the far remote geographic areas characterizing different physiographic and landscape zones of the past. As a result, the real diversity of coeval regional floras turns out to be distorted by elements of similarity that appeared artificially.

The inferable endemism degree of regional floras also depends on the amount of form genera and species identified in a given region, where the real diversity or respective taxa may be considerably lower. Let us mention here, as an example, the heuristic approach used to estimate the taxonomic diversity of ancient regional floras that is well known as "Willis distribution," according to which the majority of species belongs to the limited number of large genera, whereas most genera actually include only one or two species. Genera were similarly distributed among families, families among orders, and so on (Willis, 1922).

In addition, it is quite difficult to correlate continental flora-bearing deposits of the Angaraland with the type section of the Kazanian Stage in the Kama River basin. Most of respective correlation schemes are conditional to some extent.

In spite of the aforesaid, paleobotanical materials available now allow us to outline the geographic diversity of Kazanian floras in the Angaraland and to interpret peculiarities of the Soyana River flora. Main Angaraland regions with the known burials of Kazanian floras are shown in Fig. 1.

Pechora Basin, Neighboring Areas of the Cis-Urals, and Timan

In the Pechora basin and cis-Urals (Fig. 1, *2*), the Kazanian Stage corresponds to an upper part of the

Seida Formation coupled with the lower part of the Tal'bei Formation of the Pechora Group, or to their analogues (*Uglenosnaya...*, 1990).

The diverse plant fossils are known from this interval of the Pechora basin sequence. They are represented first of all by dominant ruflorians (family Rufloriaceae Ledran) such as *Rufloria obovata* (Neub.) S. Meyen, *R synensis* (Zal.) S. Meyen, *R. sylovaensis* (Neub.) Ignatiev comb. nov. (basionim *Noeggeratiopsis sylovaensis* Neuburg, 1965, pp. 37–38, Plates XVIII, XIX and XXXVIII, figs. 4, 4a), *R.* sp. with fine dorsal furrows, *Suchoviella synensis* Ign. et S. Meyen, *Pechorostrobus bogovii* S. Meyen, *Bardocarpus synensis* Dombr., and *B. superus* Neub. The associated vojnovskyans (family Vojnovskyaceae S. Meyen) are *Cordaites candalepensis* (Zal.) S. Meyen, *C. clercii* Zal., *C. brevis, Vojnovskya* spp., *Lepeophyllum* spp., *Crassinervia* spp., *Samaropsis erunakovensis* Radcz., *S. irregularis* Neub., and *Sylvella* sp. The next group of cardiolepidians (family Cardiolepidaceae S. Meyen) includes *Phylladoderma arberii* Zal., *P.* spp., *Permotheca* spp., *Cardiolepis piniformis* Neub. emend. S. Meyen, and *Nucicarpus piniformis* Neub.

Dominant in some burials are callipterids *Rhachiphyllum (al. Callipteris) adzvense* (Zal.) Naug., *Compsopteris adzvensis* Zal., *C. tchirkovae* Zal., *Comia dobrolubovae* Tschal., *C. latifolia* Tschal., *C. pereborensis* Zal., *Lopadiangium* spp., and *Nucicarpus* spp., all associated with leaves of pteridosperms of unclear taxonomic position *Zamiopteris elongata* (Zal.) Neub. and *Z. rossica* (Zal.) Neub. Ginkgophytes *Rhipidopsis* sp. are less abundant like pteridosperms *Pursongia* spp. and *Glottophyllum* sp., or *Wattia* Mamay (*W. erjagensis* Pukh. and *W. rara* Pukh.). Mosses are abundant at particular localities. Taxa *Asterotheca* spp., *Orthotheca petschorica* Fef., *Pecopteris helenaeana* Zal., *P. compta* Radcz., *P. micropinnata* Fef., *P. obtusa* Radcz., *P. synica* Zal., *P. varsanofievae* Zal., *P. venusta* Radcz., and *Prynadaeopteris karpovii* Radcz. represent the diverse ferns. Dominant among aquatic and semiaquatic plants are articulates *Paracalamites frigidus* Zal., *P. decoratus* (Eichw.) Zal., *P.* spp., *Tchernovia* sp., and *Sciadisca petschorensis* Zal.

The same floral assemblage is characteristic of Kazanian deposits in adjoining areas of the cis-Urals and Timan, but cardiolepidians are less abundant here. Additional taxa in these areas are ginkgophytes *Rhipidopsis ginkgoides* Schm., *R. laxa* Zal., and *Sporophyllites petschorensis* (Schm.) Fef. emend. S. Meyen; pteridosprms *Acophyllum woeltzii* Zal., *Pereborites rarinervis* Zal., *Rossovites petschorensis* Zal., *R. linguaefolius* Zal., and *Glottophyllum synense* Zal.; dicranophylls (order Dicranophyllales) *Slivkovia* sp. Leaves *Ginkgophyllum* sp. and seeds of the *Jordania* Fiedler type were encountered as well.

Two types of forest formations were dominant in the Pechora basin and cis-Urals during the Kazanian time. In the "cordaitean" one, the dominant layer and underwoods consisted mainly of ruflorians and vojnovskyans, whereas ferns prevailed in the discontinuous grass cover (*Cordaito brevis–Ruflorietum sylovaensis* Ign. and *Cordaito candalepensis–Ruflorietum synensis* Ign. plant associations). The next "phylladoderm" formation corresponded to the *Phylladodermetum arberi* Ign. plant association (Ignat'ev, 1991, 1992, 1993) that represented pure or almost pure stands of cardiolepidians, which occupied dozens square kilometers of swampy lowlands and floodplains. It was the parental vegetation that gave rise to most productive coal seams in the upper part of the Seida Formation and at different levels of the Tal'bei Formation (Pechora Group), as well as in their analogues.

Novaya Zemlya and Kolguev Islands

The Kazanian floral assemblage similar to that from coeval deposits of the Pechora basin and cis-Urals is known from the lower Gusinaya Zemlya Subformation and overlying Shadrovo Formation of the Novaya Zemlya Islands (Fig. 1, *3*; Kalashnikov *et al.*, 1981). Vojnovskyans *Cordaites iljinskiensis* (Radcz.) S. Meyen, *C.* cf. *coneinnus* (Radcz.) S. Meyen, *C. singularis* (Neub.) S. Meyen, *Lepeophyllum trigonum* Neub., *Nephropsis* spp., *Sylvella* spp., and *Cordaicarpus* spp., together with ruflorians *Rufloria synensis* and cardiolepidians *Phylladoderma arberii, P.* spp., *Cardiolepis piniformis* and *Nucicarpus piniformis* are dominant in this assemblage. Conifers have not been detected in the islands. Dicranophylls are represented by *Entsovia* cf. *rarisulcata*, and callipterids by *Rhachiphyllum (al. Callipteris)* sp. Among ginkgophytes, there were identified *Rhipidopsis ginkgoides, Ginkgophyllum vsevolodii*, and *G.* sp. Pteridosprms *Rhaphidopteris praecursoria* of a "Mesozoic habit" are also characteristic of the flora under consideration.

The pteridophyte group includes lycophytes *Signacularia* sp. and *Viatscheslaviophyllum vorcutense* Neub., ferns *Pecopteris* cf. *anthriscifolia* (Goepp.) Zal., *Prynadaeopteris karpovii*, and *Orthotheca* sp., and also articulates *Paracalamites frigidus* and *P. decoratus.*

The Kazanian flora from borehole sections of the Kolguev Island (Fig. 1, *4*) also corresponds to the Pechora biofacies. In particular, Meyen identified here vojnovskyans *Cordaites candalepensis* and *Samaropsis* cf. *irregularis*, and also callipterids *Rhachiphyllum (al. Callipteris)* sp.

Arctic North America (Canada and Alaska)

Flora resembling that of the Pechora region adjacent to the Urals is known from the northeastern Greenland. Wagner *et al.*, (1982) described and pictured here remains of ferns *Pecopteris venusta* Radcz. and *P.* cf. *helenaeana* Zal., and also *Rhipidopsis* leaves that have relatively narrow, elongated segments of leaf lamina and associate with cordaitean leaves. The latter were originally classed with *Cordaites* cf. *sylovaensis*, but in

our opinion, it appears to be more correct to attribute them to *C. candalepensis*. Articulates *Sphenophyllum* cf. *biarmicum* Zal. and conifers *Bardella* sp. were also listed in that flora composition, though without the corresponding descriptions and pictures. Accordingly, it is impossible to check the correctness of the last taxa identifications.

More recent data on flora from Greenland show that it includes as well lepidophytes of the group *Signacularia* Zal. and their dispersal phylloids *Viatscheslaviophyllum* Zal. In addition, leaves occurring in this flora were classed with pteridosperms *Pursongia* sp. and with vojnovskyans *Cordaites candalepensis* and *Lepeophyllum adzvense* (Lausberg, 1997; Wagner *et al.*, 1999).

In the western hemisphere, Late Permian floras with elements characteristic of the Angaraland are known from northern areas of American continent. Mamay and Reed (1984) described a peculiar floral assemblages from the Mount Dall Formation of central Alaska, where the corresponding terrigenous deposits of presumably Permian age yield several forms attributed to the genus *Zamiopteris* of the Angaraland type.

The Late Permian palynofloras with the Angaraland taxa are detected as well in Arctic Canada (Utting and Piasecki, 1995). Some plants typical of the Angaraland are known from the floral assemblage of the Permian Sabina Bay Formation of the Canadian Arctic Archipelago.

Western cis-Timan

In this region (Fig. 1, *5*), the diverse flora is characteristic of the Chev'yu and Veslyana formations correlated with the lower and upper Kazanian substages (Plotnikov and Molin, 1969; Molin and Koloda, 1972; Murav'ev *et al.*, 1975; Varyukhina *et al.*, 1981; Meyen, 1997).

Meyen, who summarized all data on floral remains from the Chev'yu Formation exposures along the Vym', Koin and other rivers of the region, identified in the flora composition the following taxa: vojnovskyans *Cordaites candalepensis*, small-leaved *Cordaites* sp. and *Crassinerva* sp.; ruflorians *Rufloria synensis* (Zal.) S. Meyen and *R.* sp. with narrow dorsal furrows; dispersal cordaitanthalean seeds (order Cordaitanthales) *Samaropsis* sp. and *Sylvella* sp.; dicranophylls *Mostochkia gomankovii* Smoller et S. Meyen, *Entsovia lorata* S. Meyen, *E. rarisulcata* S. Meyen, and *E.* sp.; callipterids *Rhachiphyllum* (al. *Callipteris) adzvense*, and *Compsopteris adzvensis*; peltaspermous pteridosperms *Peltaspermopsis* sp., *Permotheca* sp., and *Nucicarpus* sp.; pteridosperms of the "Mesozoic habit" "*Odontopteris*" *rossica* Zal. [= *Rhachiphyllum wangenheimii* Fisher (Naug.)], *O.* sp., *Psygmophyllum nesterenkoi* Zal., Burago, *P.* sp., *Rhapidopteris praecursoria* S. Meyen, *R.* sp., *Taeniopteris* sp., and *Stenopteris* spp.; ferns *Pecopteris helenaeana* Zal. and *P.* sp.; lycophytes *Signacularia* sp.; articulates *Equisetites* sp., *Paracalamites kutorgae* (Gein.) Zal., *P. similis* Zal., *P.* sp., and *Paracalamitina* sp.; leaves presumably characterizing pteridosperms *Pursongia* sp. and *Wattia* sp.

The Veslyana Formation yields a similar assemblage. At this level, Meyen and Goman'kov identified vojnovskyans *Cordaites candalepensis* and *C.* cf. *gracilentus*, dicranophylls *Entsovia rarisulcata*, callipterids *Rhachipyllum (al. Callipteris)* resembling in morphology the forms typical of the Pechora Group in the eponymous basin, and also ferns *Pecopteris synica* and *P. varsanofievae* typical of the same group. The associated taxa are: pteridosperms *Psygmophyllum* cf. *expansum* and *P.* sp.; peltaspermous pteridosperms (family Peltaspermaceae) *Peltaspermopsis* sp.; articulates *Paracalamites decoratus, P.* sp. and *Phyllotheca* sp.; lycophytes *Signacularia (?)* sp. and *Viatscheslaviophyllum* sp.; and mosses.

At the current stage of knowledge, it is impossible to discriminate the floral assemblages of the Chev'yu and Veslyana formations.

Kazanian floras from the cis-Timan localities and Pechora region adjacent to the cis-Urals are very similar. The ruflorians, vojnovskyans, callipterids, and ferns of both floras include many taxa in common. At the same time, the former region reveals a greater abundance of dicranophylls, *Wattia*, and pteridosprms that are of "Mesozoic habit." At the same time, *Acophyllum. Glottophyllum, Pereborites, Rhipidopsis*, and *Sporophyllithes* genera typical of the Pechora region are missing from the cis-Timan flora. Moreover, this flora includes conifers, and its subordinate cardiolepidians were of a distinct xerophyte habit. It is likely that the last group did not form an independent plant formation, because their small and narrow phylloclades (*Phylladoderma*) occur sporadically only in phytocoenoses with the dominant ruflorians, vojnovskyans, and other gymnosperms.

Volga–Urals Region

The following taxa are characteristic of the Kazanian type flora from the Volga–Urals region (Fig. 1, *6*): lycophytes *Signacularia noinskii* Zal. and *Viatscheslaviophyllum kamiense* Esaul.; articulates *Paracalamites similis* Zal., *P.* spp., *Tchernovia striata* Neub., and *Sphenophyllum stouckenbergii* Schmalh.; ferns *Orthotheca* sp., *Prynadaeopteris* sp., *Pecopteris helenaeana, P. varsanofievae*, and *P. anthriscifolia*; pteridosperms *Rhachiphyllum wangenheimii* (Fischer) Naug *"O." rossica* Zal.), *Psygmophyllum nesterenkoi* (Zal.) Burago, *P.* spp., *Rhipidopsis* aff. *ginkgoides* Schm., and *Pursongia* sp.; cardiolepidians *Phylladoderma volgensis* Esaul., *P. meridionalis* S. Meyen, *P. sentjakensis* Esaul., *Cardiolepis sentjakensis* Esaul., *Permotheca sardykensis* Zal., *P. vesicasporoides* Esaul., *Nucicarpus tarlovskiensis* Esaul., *N. sentjakensis* Esaul., and *N. minutus* Esaul.; peltaspermous pteridosperms *Peltaspermum* sp.;

vojnovskyans *Cordaites candalepensis* (Zal.) Radcz. and *Sylvella heteromorpha* Esaul.; dicranophylls *Meristophyllum* cf. *sojanaeanum* Zal. (= *Entsovia rarisulcata* S. Meyen) and *Slivkovia* sp.; conifers *Pseudovoltzia cornuta* S. Meyen and *Concholepis* cf. *harrisii* S. Meyen; roots *Radicites sentjakensis* Esaul.; and *Zamiopteris* sp.

In the Kama River localities, vojnovskyans occur only in the lower Kazanian deposits being dispersed throughout the stage sequence in the southern cis-Urals (Meyen, 1982).

Three principal types of oryctocoenoses presumably corresponding to parental plant communities were distinguished in the region under consideration: (1) one with dominant articulates *Sphenophyllum stoucken-bergii, Paracalamites frigidus, P. similes, P. decoratus,* and *Phyllotheca* sp.; (2) the second with dominant cardiolepidians *Phylladoderma meridionalis* and *P. volgensis;* (3) and the third oryctocoenosis of the mixed type (Vladimirovich, 1984; Esaulova, 1986, 1996).

Judging from the host rock facies and plant composition, the first oryctocoenosis corresponds to the aquatic community of hydro- and hygrophytes, and the second one characterizes the terrestrial plant assemblage dominated by cardiolepidians. The third oryctocoenoses includes remains of coniferous *Pseudovoltzia cornuta,* which prevail in some burials. The indicated taxa of aquatic and terrestrial plants also present in the third oryctocoenosis.

In contrast to wide and flattened leaves of the *Phylladoderma* forest formations grown in the Pechora basin and cis-Urals, cardiolepidians from localities of the Kama region were of a distinct xerophyte habit: their leaf organs were narrow, sometimes awl-shaped to ramal, and having small terminal blades. Fragments of leafy *Phylladoderma* shoots from this region show all transitions from their axial elements to the indicated leafy morphotypes. Accordingly, we assume that those were phylloclades, i.e., shoots transformed into the leaf-like structures, but not the true leaves. Development of phylloclades is characteristic of many succulents adapted to arid habitat environments. The phylloclade-bearing shoots of cardiolepidians from the Kama region were described by V.P. Vladimirovich as *Quasistrobus ramiflorus* Vlad. (see in *Atlas...*, 1986, p. 36, Plate 153, figs. 2–3).

Kuznetsk and Tunguska Basins

In the central Angaraland separated by mountain ridges from the Tethyan coast and Kazanian sea, the forest formation that controlled the general aspect of Kazanian vegetation was the so-called "cordaitean taiga." The cordaitean flora from the Kuznetsk and Tunguska basins is considered as classical example characterizing this vegetation.

The lower and upper Kazanian Substages of the Kuznetsk basin are correlated with the Kazankova–Markina and Uskat horizons of the Il'inskoe Subgroup (*Resheniya...*, 1982).

The Kazankova–Markina floral assemblage is dominated by cordaitanthaleans, mainly by small-leaved vojnovskyans and ruflorians, such as *Rufloria brevifolia* (Gorel.) S. Meyen, *R. mitinensis* (Gorel.) S. Meyen, *R. minuta* (Radcz.) S. Meyen, *R.* sp., *Cordaites gracilentus* (Gorel.) S. Meyen, *C. gorelovae* S. Meyen, *Crassinervia elliptica* Radcz., and *Cladostrobus lutuginii* Zal. emend. S. Meyen. These forms associate with dispersal cordaitanthalean seeds classed with *Tungussocarpus tychtensis* (Zal.) Such., *T. elongatus* (Such.) Such., *Samaropsis erunakovensis* Radcz., *S. irregularis* Neub., *Sylvella dubia* Such., *Condomajella gorelovae* Such., and *Cordaicarpus petrikensis* Such. According to data of S.G. Gorelova (see in Betekhtin *et al.*, 1988), other characteristic taxa of the flora under consideration are as follows: pteridosperms *Glottophyllum elongatum* Radcz., *G. karpovii* Radcz., and *Tychtopteris primitiva* Gorel.; mosses *Polyssaievia spinulifolia* (Zal.) Neub; ferns *Pecopteris pseudomartia* Radcz., articulates *Annulina iljinskiensis* (Radcz.) and *Paracalamites iljinskiensis* Gorel.

The Uskat floral assemblage is similar in general to that described above. Being also dominated by small-leaved ruflorians and vojnovskyans, it is simultaneously enriched in ferns *Prynadaeopteris nataliana* Gorel. and in callipterids *Rhachiphyllum (al. Callipteris) adzvense* and *R. (al. C.) zeillerii* (Zal.) Naug. This level also marks the first occurrence of sulcate cordaites, which become widespread in higher Permian horizons. This diversity increase seems to be a consequence of an episodic climatic warming.

Among other characteristic taxa of the Uskat flora, we should mention ruflorians *Rufloria olzerassica* (Gorel.) S. Meyen, vojnovskyans *Cordaites kuznetskianus* (Gorel.) S. Meyen and *Nephropsis schmalhausenii* Radcz., articulates *Schisoneura sibirica* Neub. and *Koretrophyllites grandis* Gorel., as well as dispersal seeds *Samaropsis grjasevii* Such. (Data of Gorelova in Betekhtin *et al.*, 1988).

The Kazanian Stage of the Tunguska syneclise (Fig. 1, *8*) corresponds to the Vekhnyaya Pelyatka Subhorizon (*Resheniya...*, 1982). The respective regional flora is close in composition to that from the Kuznetsk basin. It includes the following main groups of taxa: vojnovskyans *Cordaites gorelovae, C. gracilentus,* and *C. mediocris* (Gorel.) S. Meyen; ruflorians *Rufloria brevifolia, R. minuta, Crassinervia elliptica,* and *C. pentagona* Gorel.; dispersal cordaitanthalean seeds *Cordaicarpus petrikensis, C. pelatkaensis* Such., and *Tungussocarpus tychtensis*; callipterids *Rhachiphyllum (al. Callipteris) altaicum* (Zal.) Naug.; pteridosperms *Pursongia tunguscana* Neub.; ferns *Pecopteris anthriscifolia*; articulates *Koretrophyllites polcaschtensis* (Chachl.) Radcz., *Phyllotheca turnaensis* Gorel., *Schizoneura sibirica,* and *Paracalamites grandis* Gorel.; mosses *Polys-*

saievia spinulifolia Neub. (data of Gorelova in Betekhtin *et al.*, 1988).

Western Verkhoyansk Region

Tolstykh (1974) suggested the Kazanian age for the lower Dulgalakh Subformation of the western Verkhoyansk region (Fig. 1, 9), where this interval of the sequence yields an impoverished plant assemblage of *Annularia* aff. *erunakovensis* Neub., *A. (?)* cf. *lanceolata* Radcz., *"Noeggerathiopsis" aequalis* (Goepp.) Zal. (one of the collecting terms used to designate vojnovskyan leaves from the Angaraland), and seeds *Tungussocarpus tychtensis.*

It is likely that the lower beds of the upper Dulgalakh Subformation are also of the Kazanian age. In these beds, Meyen identified the following plant taxa: vojnovskyans *Cordaites candalepensis, C.* cf. *angustifolius* (Neub.) S. Meyen, *C. chachlovii* (Gorel.) S. Meyen, *C. gorelovae* S. Meyen, *C. gracilentus, Crassinervia* sp., *Lepeophyllum gemmatum* Radcz., *L. rotundatum* Radcz., and *L.* sp.; ruflorians *Rufloria* cf. *minuta* (Radcz.) S. Meyen, *Tungussocarpus tychtensis*, and *Samaropsis* sp.; ferns *Caulopteris* sp.; articulates *Phyllotheca* ex gr. *turnaensis, Phyllotheca* sp., and *Schizoneura czecanowskii* Rassk. In opinion of Meyen, this flora is correlative with that from the Il'inskoe and Leninsk horizons of the Kuznetsk and Tunguska basin, and accordingly, it is of the late Kazanian age.

Another assemblage recognized by Meyen in coeval deposits that are exposed in lower courses of the Lena River consists of the following plant remains: vojnovskyans *Cordaites candalepensis, C.* cf. *angustifolius, C. clercii, C. gorelovae, C. gracilentus, C.* cf. *oblongifolius, Lepeophyllum gemmatum, L. rotundatum, L.* spp., *Crassinervia* sp., *Niazonaria stellata* Radcz., *Samaropsis irregularis, S.* sp., and *Sylvella* sp.; small-leaved ruflorians *Rufloria* sp. and *Tungussocarpus tychtensis;* ferns *Pecopteris* sp.; articulates *Annularia erunakovensis, Paracalamites* sp., *Phyllotheca* ex gr. *turnaensis*, and *Schizoneura* sp. The Kazanian age of this flora is proved by finds of ammonoids (Andrianov, 1985).

The Kazanian flora of the western Verkhoyansk region is lacking callipterids and pteridosperms of the "Mesozoic habit," and ferns were less abundant here than in central areas of the Angaraland (Meyen, 1982). Plant fossils are less frequent in this region. They do not occur as mass accumulations in separate laminae, and we assume that the biomass productivity of regional plant formations was not so high. The same factor was likely responsible for a weak development of peat-forming processes in the region.

Thus, one can see that northern areas of the Angaraland retained the cordaitean type of vegetation characteristic of the Kuznetsk and Tunguska basins, but the diversity of flora and its productivity gradually decreased in the northern direction. It seems that the more favorable habitats in river valleys compensated the cooling factor, and the "cordaitean taiga" massifs were able to penetrate, though in the impoverished state, far to the north. Phytogeographic trends of this kind define the so-called "advance rule," according to which "the appearance of species or phytocoenoses in flat interfluve is advanced, further to the south or to the north, by their development in corresponding habitats" (Alekhin, 1989, p. 38).

Soyana River

The Soyana River flora of the early Kazanian time (Plates I–II, Figs. 2–4) is most similar to and genetically interrelated with floras of the Pechora basin and neighboring areas adjacent to the Urals and Timan. Its cordaitanthaleans (ruflorians *Rufloria sylovaensis* and vojnovskyans *Cordaites* sp., *Crassinervia* sp., and *Lepeophyllum* sp.) are similar in habit to those of the Pechora region. The dispersal seeds of gymnosperms are represented by the same morphotypes in all areas under comparison, but they are larger at the Soyana River site and correspond here, except for *Cordaicarpus* sp., to several new species: *Sylvella* sp. nov., *Jordania* sp. nov., and *Samaropsis* spp. nov. Remains of archaic pteridosperms *Cardioneura* ex gr. *vorcutense* that are typical of the upper units of the Vorkuta Group (analogues of the Kungurian Stage) also suggest similarity between the Soyana River and Pechora floras.

In contrast to its counterparts from the Pechora basin and cis-Urals, the Soyana River flora includes conifers *Cyparissidium* sp., the sterile shoots of which resemble those of *Timanostrobus muravievii* from Kazanian deposits occurring westward of the Timan (Meyen, 1997).

Dicranophylls from the site under consideration are represented by *Entsovia* cf. *rarisulcata* that was classed by Zalessky (1937) with *Meristophyllum sojanaeanum* Zal. characteristic of Kazanian deposits in the Kama River basin and westward of the Timan.

Representatives of cardiolepidian *Phylladoderma* sp. (Plate II, fig. 1) are similar in morphology to this taxon from the western cis-Timan.

Lepidophytes are represented by isolated sporophylls similar to *Viatcheslavia* Zal. and *Sadovnikovia* Naug. known, respectively, from the upper part of the Vorkuta Group of the Pechora basin and from the Kungurian deposits of the central cis-Urals (Naugol'nykh, 1994, 1998). They also resemble the dispersal phylloids *Viatscheslaviophyllum* cf. *kamiense* from the Kazanian deposits of the Kama River basin (Esaulova, 1986).

Other pteridophytes are of the archaic Euramerian habit. The distinguished ferns are classed with the European taxa *Pecopteris* ex gr. *leptophylla* Bunbury and *Lobatopteris* sp.

As for *Pecopteris* ex gr. *leptophylla*, we attributed to this taxon the last-order pines and a fragment of bipin-

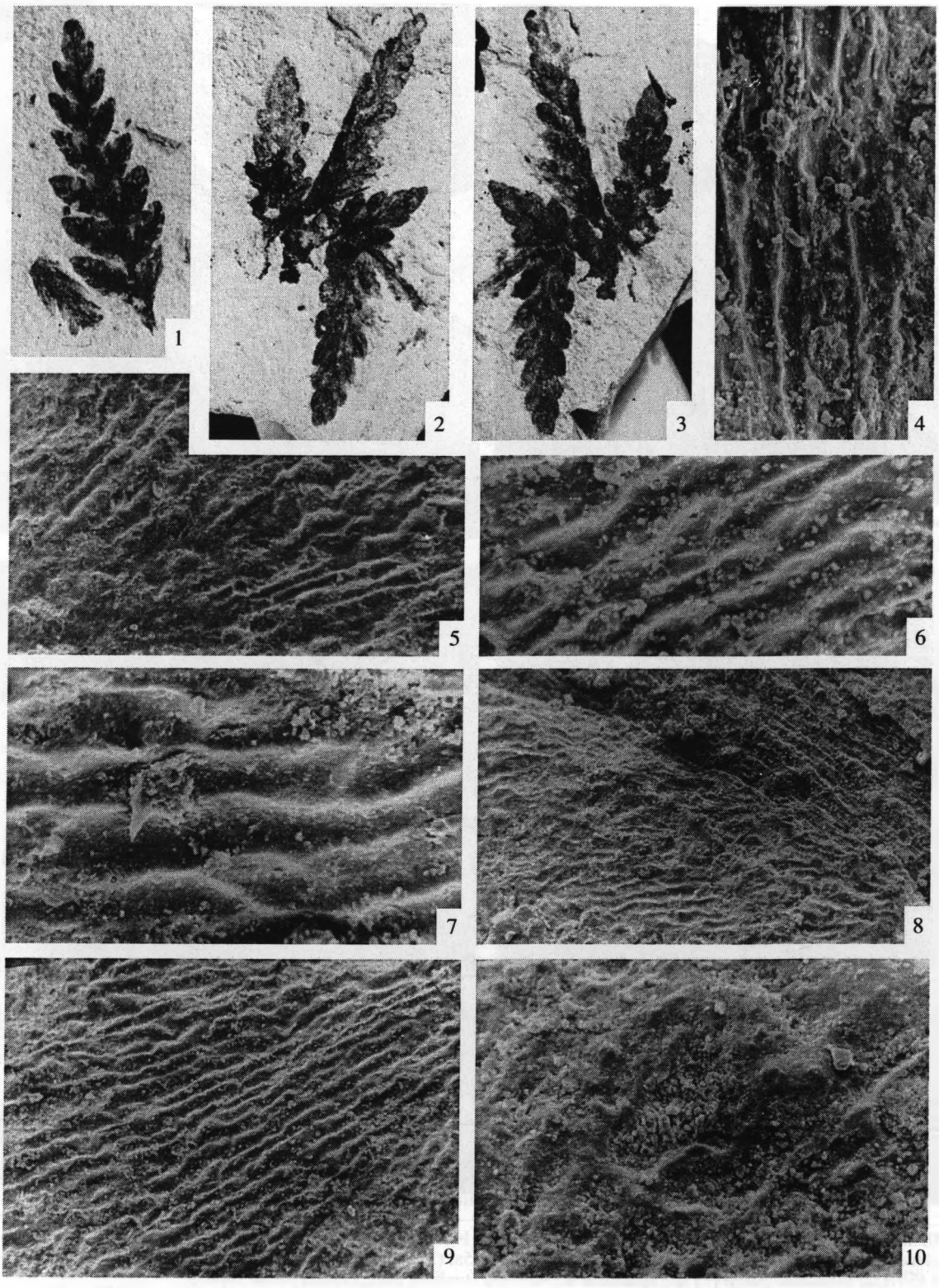

Plate I. *Pecopteris* ex gr. *leptophylla* Bunbury (the Iva-Gora site, lower Kazanian Substage): (1) pine of the last order, specimen no. 4547/28, ×3; (2, 3) pines of the penultimate order, ×3, specimen nos. 4547/29a (2) and 4547/29 (3); (4) elongated cells of the costal area, ×270; (5) two costal areas with elongated cells and one intercostals area with more isometric cell having bended margins, ×150; (6, 7) cells of costal area, ×270; (8) contact zone between epidermis of the leaf blade (below left) and that situated above the midrib of pinnule (above right), ×75; (9) epidermal structure in basal part of the decurrent catadromous margin of a pinnule, ×150; (10) stoma, ×270.

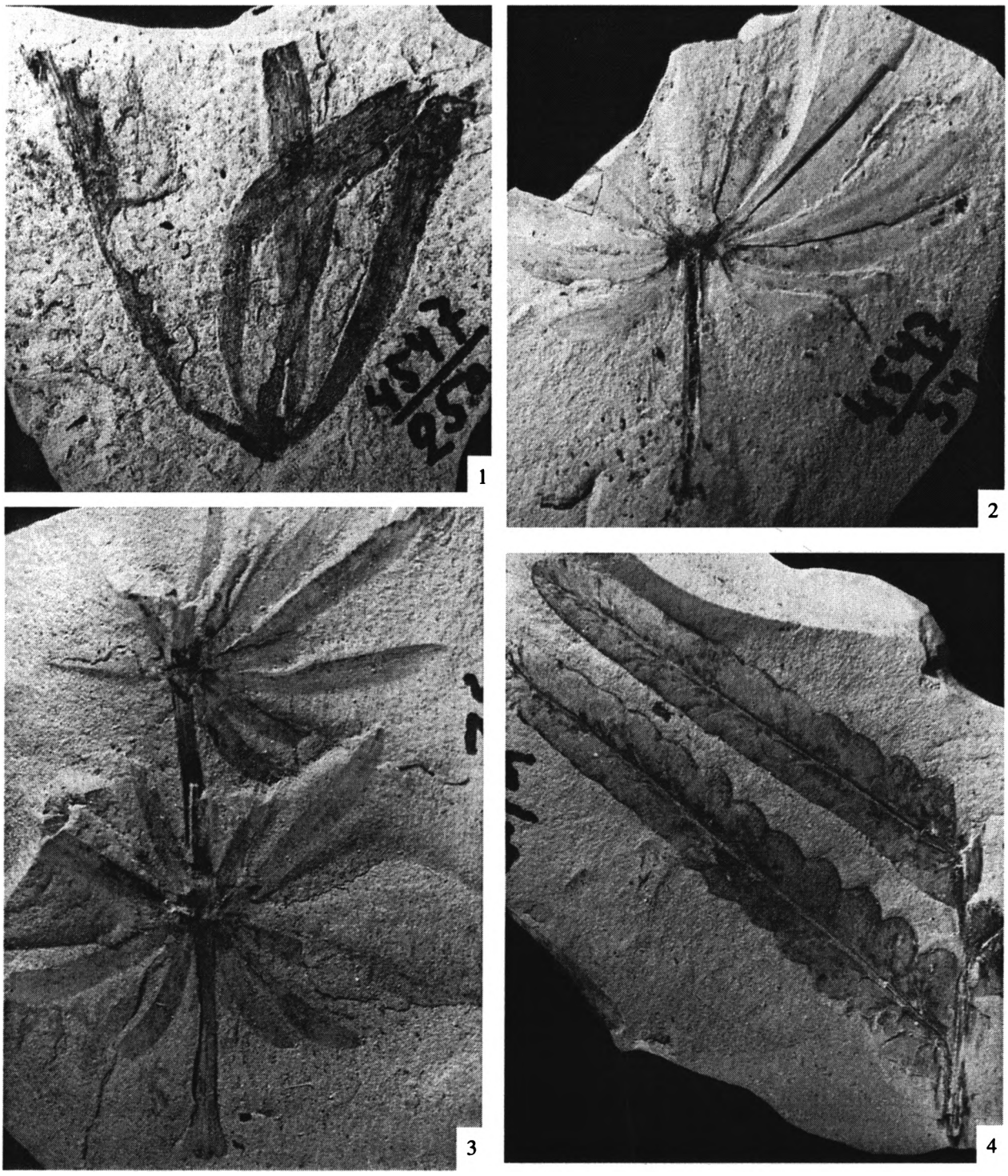

Plate II. Some taxa of the early Kazanian Soyana River flora (the Iva-Gora site, lower Kazanian Substage): (1) *Phylladoderma* sp., phylloclades clustered in the terminal whorl, specimen no.4547/25a; (2, 3) *Annularia* aff. *carinata* Gutbier, specimen nos. 4547/34 (2) and 4547/32; (4) *Lobatopteris (?)* sp., specimen no. 4547/30 (twofold exaggeration for all forms).

nate frond (Plate I, figs. 1–10; Figs. 2a–2c, 3). Each pine has 5 to 7 pairs of subtriangular pinnules, which are coalescently fused as a rule. The venation patterns of pinnules consist of a well-developed median vein and two-three pairs of lateral feathery veins, which alternately deviate from the former. Examination under the scanning electron microscope showed that the epidermis of pinnules is differentiated into costal and intercostals areas. The elongated costal cells are rectagonal in shape; their centroclinal walls are slightly undu-

Fig. 2. Pteridophytes of the Soyana River flora. *Pecopteris* ex gr. *leptophylla* Bunbury: (*a*) middle part of the penultimate-order pine with broken rachis, specimen no. 4547/29; (*b*) topside pine of the last order with poorly differentiated, coalescently fused pinnules, specimen no. 4547/50 the lower part of which was used as preparation for examination under the scanning electron microscope; (*c*) mature pine of the last order, specimen no. 4547/28. *Lobatopteris (?)* sp.—(*d*) frond fragment with basal parts of last-order pines, specimen no. 4547/30, and (*e*) character of venation in pinnules: *1*, initial vein producing the anadromous (acroscopic) and catadromous (basiscopic) branches; *2*, acroscopic branch dichotomizing to form the midrib of pinnule; *3*, dichotomizing midrib; *4*, next stage of midrib branching, when catadromous vein may branch simultaneously (scale bar 2 mm, the Iva-Gora site, lower Kazanian Substage).

lating. Their size is equal in average to 150 × 30 μm. The intercostals cells are more isometric in shape, having the average size of 50 × 30 μm. The superficial, irregularly oriented stomata have subsidiary nonspecialized cells. The described remains are very similar to sterile leaves of *Oligocarpia leptophylla* (Bunbury) Grauvogel-Stamm et Doubinger, the species characteristic of Lower Permian deposits in western and central Europe. Taking into consideration, however, that the fertile leaves of described forms are unknown, we attribute them to *Pecopteris* ex gr. *leptophylla* Bunbury, the form species characterizing fronds with the unknown structure of sporangia.

Among small fragments of sterile pines from the Iva-Gora locality, which probably belong to *P.* ex gr.

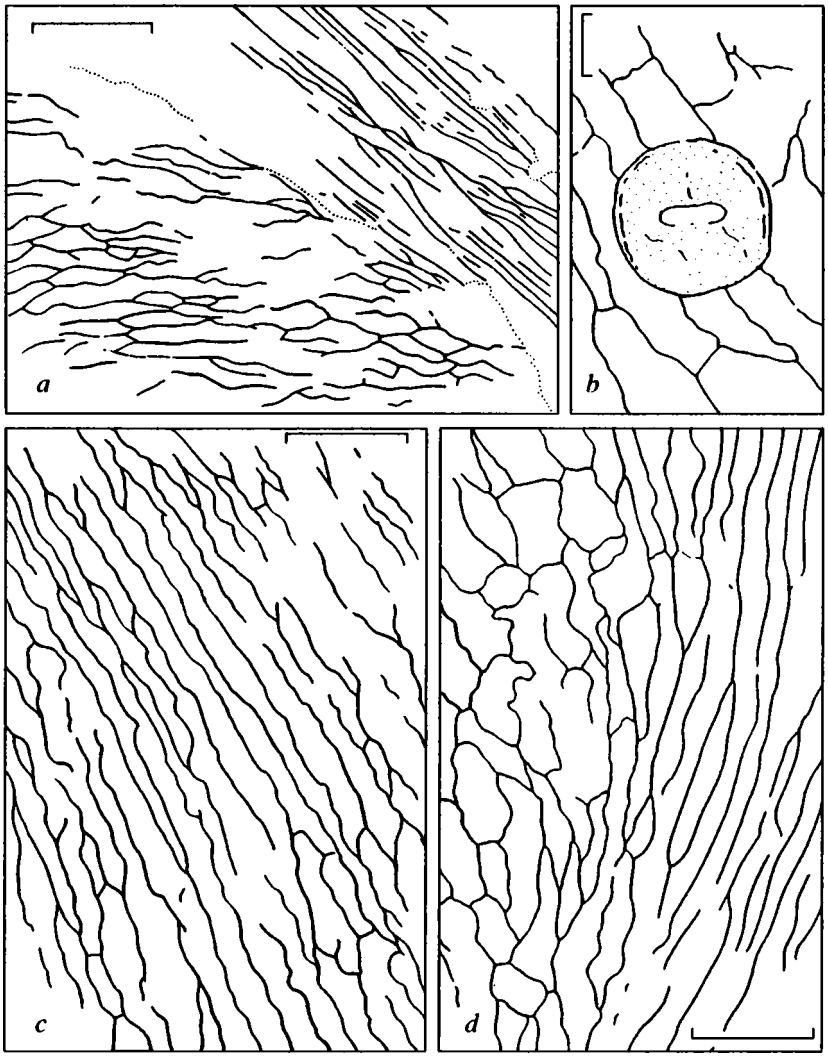

Fig. 3. Epidermal structure in basal part of the last-order pine of pteridophyte *Pecopteris* ex gr. *leptophylla* Bunbury (specimen no. 4547/50) from the Soyana River flora (Iva-Gora site, lower Kazanian Substage): (*a*) contact zone between epidermis of the leaf blade (below left) and epidermis situated above the pinnule midrib (above right, scale bar 200 μm); (*b*) stoma (scale bar 40 μm); (*c*) epidermis of the costal area (scale bar 100 μm); (*d*) contact zone between costal (right) and intercostals (left) areas (scale bar 100 μm).

leptophylla, Zalessky (1937, pp. 92–92, Figs. 62–64) identified three new species: *Pecopteris coserrata* Zal., *P. attenata* Zal., and *P. spiculosa* Zal. In our opinion, his identifications are needless.

The sole fragment of bipinnate frond with two pines of last order, which are preserved almost entirely, is classed here with *Lobatopteris (?)* sp. (Plate II, fig. 4; Figs. 2d, 2e). In each pine, there are 12–13 pairs of pinnules, which are closely fused along margins, thus forming the leaf blade with the unicoherent venation. The median vein is thick and short, traceable only up to the middle of the pine. Dichotomous (up to three times) lateral veins deviate from it in the featherlike manner.

Within limits of the Angaraland, similar *Pecopteris* forms are known from Lower Permian (Artinskian and lower Kungurian) deposits of the cis-Urals, and *Lobatopteris* remains were found in the Vorkuta and Pechora Groups of the Pechora basin (Molin *et al.*, 1983, pp. 48–49, Plate IX, figs. 1 and 1a).

The European species *Annularia* aff. *carinata* Gutbier identified among articulates (Plate II, figs. 2, 3; Fig. 4) is also known from Kungurian deposits of the central cis-Urals. We attribute to this taxon the leafy shoots, on which the linear leaves are clustered in whorls. As a rule, the whorls are anisophyllous, bilateral-symmetric. Leaf sheaths are absent. One whorl includes 10–14 leaves. Leaves are lanceolate, sometimes with almost parallel borders; they have acute apex and slightly narrowing base. In the middle of each leaf, there is single well-seen vein. The leaf surface is smooth. In average, leaves are from 10 to 16 mm long, and from 1.2 to 3 mm wide. Internodes are 15–18 mm long. The shoot surface is decorated with distinct lon-

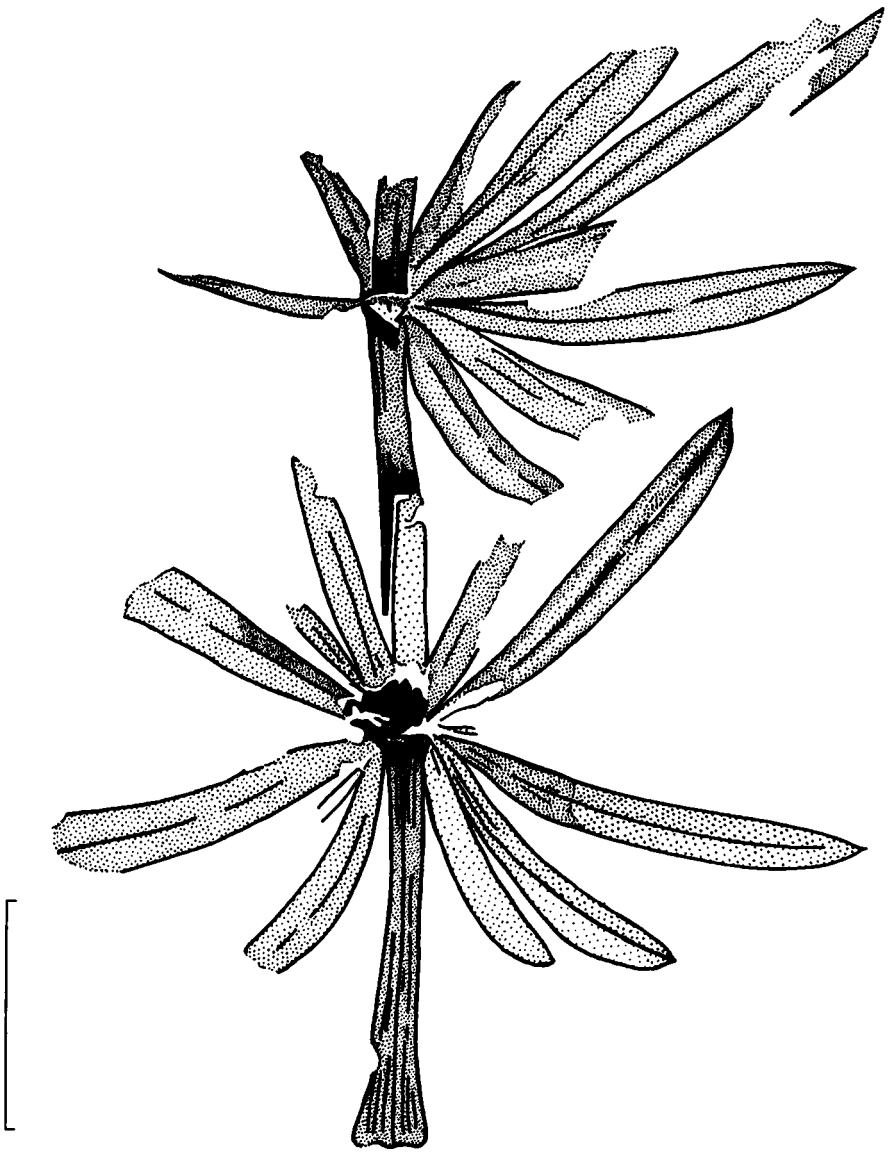

Fig. 4. A part of leafy shoot of *Annularia* aff. *carinata* Gutbier with two whorls, specimen no. 4547/32 (Iva-Gora site, lower Kazanian Substage). Note that leaves different in length are arranged bilateral-symmetrically (scale bar 1 cm).

gitudinal ribbing. Among the studied specimens, there is a fragment of leafy shoot similar to other specimens in all morphological features, but much lesser in size. This specimen presumably characterizes the terminal part of a young plant.

PHYOGEOGRAPHIC ZONING OF THE ANGARALAND DURING THE KAZANIAN TIME

According to Meyen's concept (1987a, 1987b, 1988), there are three stages of paleophytogeographic and paleofloristic investigations, which differ from each other by the extent of generalization and theorization. At the initial stage, we tend to reveal a panorama or general distribution patterns of plant remains in the study region for a given geological epoch. Panoramas of this kind can be exemplified by the well-known phytogeographic schemes of the Angaraland for the Late Paleozoic (Vakharameev *et al.*, 1970, 1978; Meyen, 1982, 1987a). The purpose of the next higher stage is to scenarize those panoramas adding to them elements of dynamics and investigating the concrete ways of the plant cover evolution. The third highest stage consists in creation of a general model that takes into consideration all particular scenarios and depicts most significant and essential events recognizable in the latter. In other words, this is a stage of creating a "universal scenario."

From the standpoint of cognitive science, the aforementioned panoramas, scenarios, and models are

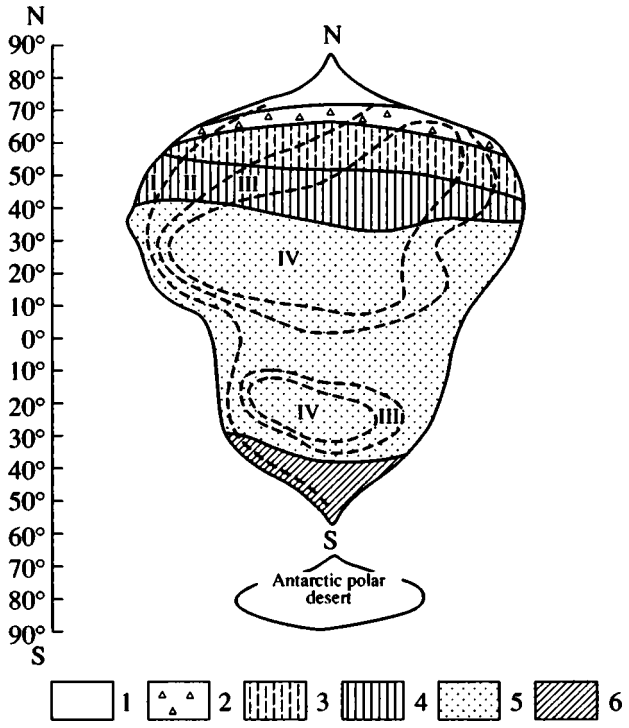

Fig. 5. A model of "ideal continent:" (1) polar deserts; (2) tundra zone; (3) boreal zone; (4) subboreal zone; (5) tropical zone; (6) southern extratropical zone. Roman figures denote subdivisions of the second order: (I) western ocean-side sector; (II) transitional moderately continental sectors; (III) typical continental sector; (IV) extreme continental sector.

hypotheses projected into the past, but based on the present-day conceptions. Basic in any reconstruction is the idea that structural or dynamic regularities in observable phenomena are invariable with time (principle of uniformity) and can be projected into the geological past in accord with the following statement: "the present is the key to a past situation" (actualism). In paleophytogeography, these are static and dynamic regularities in the landscape-geographical diversity of global vegetation.

In this work, we reconstructed the vegetation zoning in the Angaraland during the Kazanian time. An earlier attempt of the same kind was done by Ziegler (1990) who tended to recognize, using the insufficiently correct approach, a system of the present biomes by Val'ter (1968) without due regard to regional floras and paleogeography of the Angaraland. In particular, he ignored the fact that the complexity and diversity of ecosystems considerably increased since the Late Paleozoic (Meyen, 1987).

In our effort to interpret fossil materials from the standpoint of invariable biosphere differentiation, primarily of its plant components, we used the model of an "ideal" or "universal" continent based on works by E. Schimper, G. Brokman-Erosch, E. Rubel, K. Troll, G.N. Vysotskii, N.I. Ivanov, and others (the detailed characteristics see in Val'ter, 1968; Isachenko, 1991; Sukachev, 1926). The model of "ideal continent" (Fig. 5) depicts the natural latitudinal differentiation of biosphere from equator to poles. The respective zoning is chiefly controlled, in addition to some other factors, by the irregular and seasonal distribution of short-wave solar energy across latitudes and by the daily rotation of the Earth, which are responsible for circulation in the atmosphere and hydrosphere. As a result, we observe large latitudinal zones on the Earth's surface, each with its own physiographic environments and macroclimate. The average annual quantity of heat and humidity, and their within-year variations control the drainage, swamping, ground-water budget, general hydrological regime, formation of weathering crusts and soils, migration of chemical elements, and principal types of plant formations.

Boundaries between zones are not static. As is noted by Isachenko (1991, pp. 68–69), "the basic and direct cause of zones displacement is macroclimatic variations, which can be controlled, in turn, by astronomic factors (fluctuations of solar activity, tilt variations of the Earth's rotational axis, and tidal forces changeable in the Earth–Moon–Sun system). Following the climate, other components of geosystems must be reorganized." For instance, the current landscape–climatic zoning originated during the Cenozoic (Meyen, 1987a), when boundaries of temperate and polar zones were most mobile. At the time of Quaternary glaciations, related cooling, and growing aridity, the displacement amplitude of boundaries was up to thousands kilometers.

The "universal" continent is an ideal model, like ideal gas in physics: it depicts some general trends of biosphere differentiation, but it cannot be considered as the complete and adequate description of the reality. The latter is complicated by changeable configurations of oceans and continents, by presence of land-locked seas and straits, and by variability of relief forms and terrestrial deposits. The "ideal continent" is simply set off the global ocean; mountain systems, inner seas and straits are removed from its surface. The model also presumes that main land areas are concentrated in the northern hemisphere. Accordingly, it shows positions of principal climatic boundaries and distribution of dominant plant formations depending on the geographic latitude and distance from oceanic coast. Our model is based on characteristic parameters of the present-day continents.

Zones distinguished within the model continent and replacing one another from the northern pole toward the equator (Fig. 5) are characterized below. In addition to geographic coordinates, main climatic parameters, and principal plant formation, we use in our description the term of "maximum growth forms" to indicate plant groups (grasses, shrubs, or trees), which are able to grow under climatic conditions of a given zone.

(1) Polar desert zone is situated between 70 and 80°N. Climate is cold, mostly humid. Vegetation cover

is underdeveloped. Maximum growth forms are low grasses.

(2) Tundra zone is limited by 60 and 70°N. Climate is cold, though slightly warmer and more humid than in polar deserts. The entire vegetation cover is admissible locally. Maximum growth forms are shrubs and undershrubs. First groups and sparse growth of dwarfed trees appear in the southern forest-tundra belt. Peat formation is poorly developed.

(3) Boreal zone of moderately cold, predominantly humid climate is located between 50 and 60°N. Forest formations with limited number of dominant taxa are widespread and influence the drainage system. Peat formation is characteristic of humid areas.

(4) Subboreal moderately warm zone extends from 40 to 50°N. Humidity and type of vegetation are highly variable, depending on the distance from ocean. Broadleaved deciduous forests are widespread in maritime areas. Further inland, they give place to forest-steppe, steppe, semidesert, and desert vegetation. Humid areas are favorable for peat formation.

Zones (3) and (4) are characterized by four thermal seasons; atmospheric precipitates are fairly uniform throughout the year, except for the summer maximum.

(5) Tropical zone of warm to hot climate is between equator and 40°N. Moistening conditions vary from humid to extra-arid. Highly variable environments give rise to a wide spectrum of plant formations—from equatorial rain forests, which are extremely diverse in taxonomic aspect (dominants included) and rich in various lianas and epiphytes, to suppressed vegetation of tropical and subtropical deserts.

The described model of "ideal continent" is applicable for interpretation of phytogeographic zoning during the Kazanian Age, if the following postulates are correct.

(1) At present and during the Kazanian time, insolation parameters of the Earth's surface were comparable.

(2) Considerable continental masses of that time were located in the northern hemisphere.

(3) Kazanian plant formations consisted, like now, of trees, shrubs, and grasses, distribution areas of which were limited by the same macroclimatic parameters.

(4) Factors that now control position, shape, and dynamics of boundaries between phytogeographic zones were the same during the Kazanian time.

In addition, we considered in our interpretation the reconstructed configuration of continents and oceans, existence of land-blocked seas and straits, distribution of main mountain systems, development of glaciations, and inferable areas of coal accumulation and evaporite sedimentation.

Figure 6 illustrates positions of some zones characterized above in the Angaraland of the Kazanian time. As the paleogeographic basis, we used the corresponding palinspastic maps drawn by Lottes and Rowly (1990) and by Nie *et al.* (1990).

The greater part of the Angaraland corresponded to the boreal zone, where cordaitean forests ("cordaitean taiga") represented principal plant formations. Eastern piedmonts of the Paleourals bounded this zone in the southwest. Another mountain system separated it from the eastern part of the Tethys. Vegetation typical of the zone is exemplified by Kazanian floras of the Kuznetsk and Tunguska basins. In terms of paleophytogeography, the cordaitean flora of central Angaraland belonged to the Angarian paleofloristic region (Meyen, 1987a) or to synonymous boreal zone.

In terms of landscape geography, the Angara boreal zone represented a hilly plain, surface of which locally approached the sea-level mark. Bogomazov *et al.* (1987, pp. 81, 87) suggested that areas of the present-day Kuznetsk and Gorlovo basins corresponded to a swampy lacustrine plain. Shallow, locally humified lakes in its central and southern parts hosted bivalves, conchostracans, and ostracodes. In the north, there was a large hard-water lake. That lacustrine plane was situated in the area of temperate humid climate.

The regime of large relict lakes (fresh-water lagoons) has set in the greater part of the Tunguska basin in response to the intense rising of eastern margin of the Siberian platform during the Late Permian (Kazanian) time. In the south, this region joined the alluvial plain that was periodically swamped and connected with the provenance of terrigenous material. In the northwest, the lakes had episodic communications with a shallow sea gulf with brackish water, the remnant basin after sea regression toward the north (Gurevich, 1987, pp. 117–119).

It is likely that the "cordaitean taiga" approached the northern Angaraland boundary, i.e., the southern coast of the Verkhoyansk sea. On the one hand, this is evident from predominance of cordaites in the Kazanian flora of the western Verkhoyansk region like in coeval floras of the central Angaraland. On the other hand, there is no sign of a considerable polar glaciation that could displace the boreal zone boundary to the south. Chumakov (1994) who investigated Upper Permian diamictites of the Atakan Formation (upper courses of the Kolyma River) showed that these rocks were deposited not only by seasonal sea ice, but also by icebergs of the outlet glacier and, possibly, by shelf glaciers as well. Considering these data, he suggested that the extreme north of the Angaraland corresponded to the cold belt. Our reconstruction similarly shows that the area located northward of the Verkhoyansk sea could actually correspond to the tundra zone. Data on the Late Paleozoic floras of the considered regions are unknown so far.

The above consideration proves the viewpoint of Meyen (1982) that the Late Permian cordaitean floras of the Vilyui syneclise and Verkhoyansk area, which are taxonomically less diverse than others, characterize an independent Tunguska–Verkhoyansk province of the Angarian paleofloristic region, where climate was fairly cold.

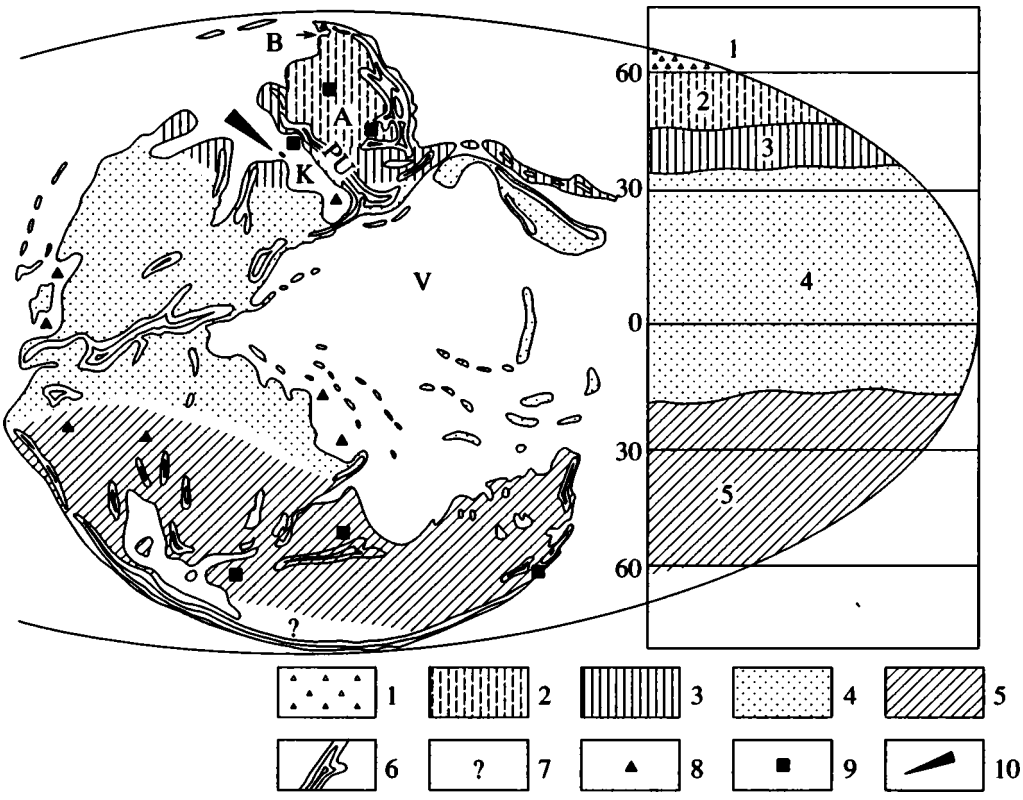

Fig. 6. Inferable phytogeographic zoning of the Earth during the Kazanian time: (1) tundra zone; (2) boreal zone; (3) subboreal zone; (4) tropical zone; (5) southern extratropical zone; (6) mountain systems; (7) areas lacking confident phytogeographic characteristics; (8) evaporite deposits; (9) sites of intense coal accumulation; (10) island (archipelago) populated by the Soyana River flora. Letter symbols indicate Angaraland (A), Paleourals (PU), Kazanian (K) and Verkhoyansk (V) seas, and the Tethys (T). Continental plates are assembled as in reconstruction by Ziegler *et al.* (1998).

The subboreal zone of the Kazanian time occupied the northwestern piedmonts and adjacent foredeep of the Paleourals, and also those areas of the Timan, Russian platform, and Arctic North America, which have not been flooded by sea. Its natural northeastern boundary corresponded to orogenic system of the Paleourals, where ridges extending in the southeastern direction were locally more that 2000 m high. The subboreal zone is characterized by Kazanian floras from the Pechora basin, cis-Urals, Novaya Zemlya and Kolguev islands, western cis-Timan, and Arctic North America. In terms of paleophytogeography, these floras characterize the Pechora province of the Angarian paleofloristic region. Partially, some of them (Kama River basin and western cis-Timan) belonged to the adjacent Subangarian paleofloristic region (Meyen, 1982, 1987a). The reconstructed zoning suggests that all these floras originated in a single subboreal zone, where they were interrelated via migration paths along the eastern coast of the Kazanian sea, or via those that appeared during regression phases of the latter. Differences between the aforementioned floras are caused by the past aridity gradient that increased in the southeastern direction.

In terms of landscape geography, the subboreal zone represented a hilly plain with the coastal lowland areas near the Kazanian sea and ocean. Bogomazov *et al.* (1987, pp. 89, 95) concluded that the present-day area of the Pechora basin corresponded to the swampy alluvial-lacustrine plain influenced by sea ingressions. Climate was variably humid and moderately warm. Shallow, fresh- or brackish-water lakes were humified periodically and populated by conchostracans, ostracodes, insects, and acritarchs. Among them, there was one immense fresh-water lagoon, with rivers flowing into it and taking origin eastward, in the Paleourals. Far in the west, within the Barents Sea plate, this lagoon periodically communicated with the sea. The lacustrine plain was a site of intense peat formation. During the accumulation period of coaliferous deposits, climate of the zone changed from semihumid (Ufimian Age) to distinctly humid (Kazanian Age). At the same time, the relative aridity generally increased from the northwest toward the southeast.

According to work mentioned above, the early Kazanian sea transgression flooded central, eastern, and southern areas of the Russian platform. Soon afterward, areas under consideration turned into alluvial lacustrine plains in response to the general regional uplift. This event isolated the region from the Kazanian

sea that degraded by the end of the Kazanian time experiencing salinization.

The Volga–Urals region with its type localities of Kazanian flora represented a zone affected by recurrent oscillatory regressions of the Kazanian sea. Variable sedimentation environments, such as alluvial, eluvial-diluvial, lacustrine, subaquatic and terrestrial deltaic, estuarine and lagoonal, were characteristic of the maritime accumulative plain that was forming at that time in this region. Numerous brackish- and fresh-water lakes were scattered throughout the plain, the latter far away from the coast. Some bitter-salty lakes near the coast line accumulated variegated clay, dolomite, and marl beds with rounded nodules of pink gypsum. Burials of plant remains, fresh-water pelecypods, ostracodes, and ganoid fishes are confined to small clay and siltstone lentils intercalated with fluvial cross-bedded sandstones. These fine-grained sediments are classed with facies of oxbow lakes occurring in river valleys of the Kazanian time (Ignat'ev, 1987, pp. 143–144). As is mentioned above, the real natural zones are not continuous belts bounded by parallels. This is a consequence of considerable changes in the thermal and moistening conditions across latitudes depending on the region position relative to the general system of continent–ocean atmospheric circulation (regional remoteness from oceanic coast), and also on the heat redistribution by sea currents. The resulting "submeridional" subdivisions are termed sectors. For instance, the western ocean-side and transitional moderately continental sectors (distribution areas of forest landscapes) are distinguished in the recent subboreal zone of western Eurasia. Further inland, parallel to the growing aridity, they are replaced by the typical continental sector with its forest-steppe and steppe landscapes. Finally, central semideserts and deserts located in subboreal zone of this continent correspond to the extreme continental sector. Sectorial subdivisions of this kind are shown as well in the model of "ideal continent."

Sectorial subdivisions are distinguished within the reconstructed subboreal zone of the Kazanian time. For instance, areas of the Pechora basin and cis-Urals can be included into the western ocean-side sector. Indicators suggesting this are the broad-leaved forest formations of cardiolepidians *Phylladodermetum arberi* Ign., which were widespread in these areas. The Kazanian floras from the western cis-Timan characterize the transitional, slightly to moderately continental sector, where conifers were frequent components of plant formations. The type Kazanian floras of the Volga–Urals region also include plant remains of the moderately continental type, but their burials in the evaporite belt originated within the typical continental sector. In this case, it is understandable, why many Kazanian taxa identified in these burials, cardiolepidians included, reveal the distinct xeromorphic morphology.

CONCLUSION

The Kazanian flora of the Soyana River site originated in the subboreal zone described above. On the basis of several characteristics, we assume that it was insular, rather than terrestrial flora. First of all, this is evident from facies transitions between the Iva-Gora Beds and typical marine sediments. Another indication is composition of aquatic and semiaquatic plants, chiefly of articulates, distinguished in the Soyana River flora. As is known, the relatively "uniform" living conditions in aqueous medium enable aquatic macrophytes to populate vast areas depending on the extension of lake and river systems. From this viewpoint, the endemic and archaic articulates of the Soyana River flora may point to a long-term geographic isolation of the latter. The large-sized seeds of gymnosperms occurring in this flora suggest a warm and humid climate, in other words, a strong influence of marine environments on vegetation of a small island that arose in the course of the Kazanian sea transgression. The long insular isolation of the Soyana River flora is also inferable from the conformable occurrence of the Iva-Gora Beds above the red continental Sheshma Horizon of the Ufimian Stage.

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Zonal Subdivisions of the Quaternary in Eastern Europe Based on Small Mammals

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Abstract—A scheme of small mammal (vole) zones is proposed for the Quaternary of Eastern Europe. The zonation is based on the evolutionary appearance of new forms in the *Borsodia–Prolagurus–Lagurus*, *Mimomys–Arvicola*, and *Allophaiomys–Stenocranius* lineages. The defined units represent the regional range or concurrent range zones. Eleven zones, four of which are subdivided into subzones, are distinguished.

Key words: *Quaternary, mammals, stratigraphy, zonal subdivision, Eastern Europe.*

INTRODUCTION

Since the moment, when Gromov (1948) distinguished successive assemblages of the Pliocene and Quaternary mammals, they were used as a basis for the subdivision and correlation of continental deposits throughout the former USSR. At about the same time, similar biostratigraphic units of the Neogene and Quaternary were defined in Western Europe and North America. In recent decades, however, biozonation gains the increasing significance in practice of subdivision of the Late Cenozoic. Zonal units originally were defined in marine sediments on the basis of fossil plankton, and the mammal zones were subsequently distinguished in continental deposits. For instance, Mein (1975) was first to propose the widely known Neogene zonation of mammal faunas, and then it was elaborated for the Quaternary (Guerin, 1982; Agusti *et al.*, 1987; Feifar and Heinrich, 1990; and others).

Unfortunately, the Quaternary mammal zones did not gain much recognition among paleontologists as some of them had poorly substantiated zonal boundaries, while others were of the comparatively wide ranges. It should be noted that the latest progress in understanding the small mammal evolution, especially of voles, enables a considerably more detailed subdivision and correlation of the Quaternary continental sediments than it was possible before. In this work, we suggest a version of the Quaternary mammal zonation in Eastern Europe.

MATERIALS AND METHODS

Paleontological records that are used as a basis for the proposed zonation are described in works by Agadzhanyan (1972, 1976, 1992), Aleksandrova (1976), Kazantseva (1987), Markova (1982, 1992), Rekovets (1994), and Tesakov (1995, 1998). The works of special significance are those by Krasnenkov and Iosifova who contributed much to a search of new localities, to collecting faunas, and to geological characterization of bone beds (*Opornye razrezy...*, 1984; *Verkhnii pliotsen...*, 1985).

We analyzed data on 51 localities of Eastern Europe (Fig. 1). Some of them are of the multilayer structure. Actually, the bone localities are much more abundant in the study region, but we focused attention on those, which are most precisely correlated with stratigraphic horizons. The taxonomic composition of voles from these localities is characterized in the table. Faunas from some localities were revised by Tesakov.

The proposed zonation is based on new forms appearing in certain phyletic lineages. Using a single lineage, we can distinguish no more than four or five range zones in the Quaternary. Since the appearance levels of new forms in different phyla do not coincide in time, several phyletic lineages that are used considerably enlarge the number of the distinguishable range or concurrent range zones. When elaborating zonation, we considered the most common and widespread forms of three phyletic lineages: *Borsodia–Prolagurus–Lagurus*, *Mimomys–Arvicola*, and *Allophaiomys–Microtus (Stenocranius)* (Fig. 2). Zonal boundaries are placed at the appearance levels of new species in a certain lineage. We defined the first occurrence level of a new species just where the abundance rate of an advanced morphotype in the assemblage is as high as 75%. It should be emphasized that the accepted value is a matter of convention and agreement. Some zones were subdivided into subzones according to the same principle with due consideration of forms belonging to other phyletic lineages. Zones and subzones are named after their index species. In addition, they are designated by the literal-numeric indices, for instance, by

MQR1, where M means mammals, Q—Quaternary, R—Russia, and the Arabic numeral is the zone number counting downward from the top. Subzones are designated by the Latin capital letters (A, B, C) in the downward succession from the top as well. When we had to subdivide a subzone, the resultant units were indicated by Arabic numerals once again downward from the top. The accepted designation system is like that of magnetic subdivisions in the latest magnetochronological scales.

The age of zonal boundaries was defined in accord with the locality position in the stratigraphic, magnetochronological, and oxygen isotope scales. The zonal boundary datums are of different reliability within certain intervals of the Quaternary. Their confidence depends on the reference locality position relative to the boundaries of paleomagnetic units, and on the validity of correlation between stratigraphic horizons and stages of the oxygen isotope scale.

POSITION OF REFERENCE LOCALITIES IN THE STRATIGRAPHIC, MAGNETOCHRONOLOGIC, AND OXYGEN-ISOTOPE SCALES

It is a customary practice to place the lower boundary of the Quaternary continental deposits at the first occurrence of rootless voles *Allophaiomys*. The Kryzhanovka 4, Tizdar 1, and Tiligul sites (Fig. 3) that yield *Allophaiomys* remains are most ancient in Eastern Europe. The Zhevakhova Gora 5 and 9, Chortkov, and Tizdar 2 localities are somewhat younger and reveal association of archaic *Allophaiomys* form with *Lagurodon arankae* and *Prolagurus ternopolitanus*. All these localities are assigned to the Zhevakhova Gora Horizon in the stratigraphic scheme by Nikiforova and Aleksandrova (1991). In their scheme, the Zhevakhova Gora Horizon is placed just below the Jaramillo Subchron, though it seems to be older than the Olduvai Subchron, because the Tizdar 1 and 2 sites are localized at the Kuyal'nik level, and the Kuyal'nik–Gurian boundary runs in the middle of the Olduvai Subchron (Pevzner, 1989; Pevzner *et al.*, 1998).

A group of localities, e.g., the Korotoyak 3a, Akkulaevo (the Dema and Davlekanovo horizons), Uspenka, and Log Denisov, yield the *Allophaiomys* form intermediate between *A. deucalion* and *A. pliocaenicus*. The exact stratigraphic position of the localities is unknown. They fall in the interval between the Olduvai Subchron and the Nogaisk Horizon base. The younger Tarkhankut locality that yields the more advanced *Allophaiomys pliocaenicus* is referred to the same stratigraphic interval.

The next group of localities is assigned to the Nogaisk Horizon included by Nikiforova and Aleksandrova in their scheme. The lower boundary of the horizon coinciding with that of the Taman' faunal assemblage (nomenclature by Gromov) is dated back to 1.2 Ma (Vangengeim *et al.*, 1991). The base of the horizon is defined by the appearance of *Prolagurus pannonicus*, and its top is marked by the appearance of *Stenocranius ("Pitymys") hintoni* and *Clethrionomys glareolus*. The most ancient Nogaisk and Korotoyak 3c localities of the group are situated in uppermost beds of the Uspenka Formation, where *Prolagurus pannonicus* appears among voles.[1] The Zapadnye Kairy, Ushkalka,

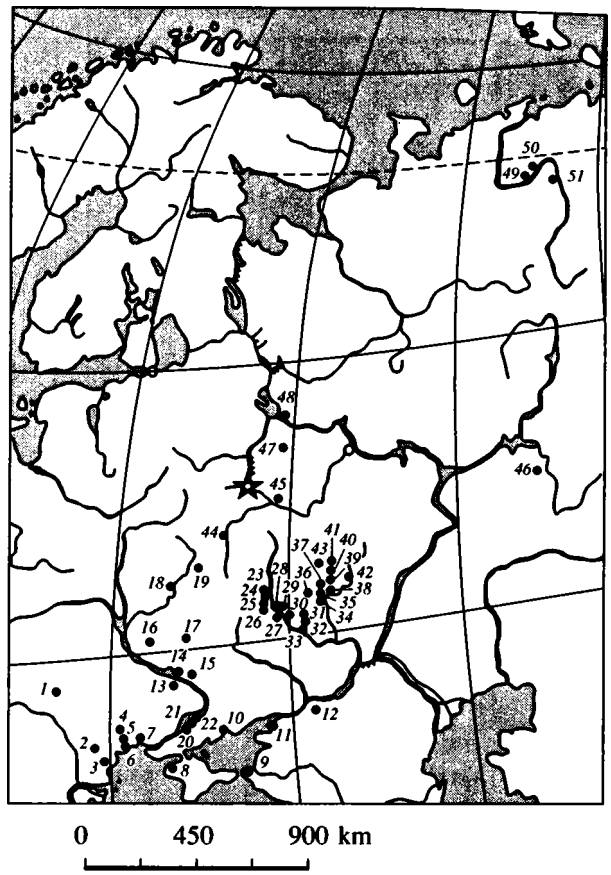

Fig. 1. Geographic map of mammalian reference localities: (*1*) Chortkov; (*2*) Kolkotova Balka; (*3*) Roksolany; (*4*) Morozovka; (*5*) Zhevakhova Gora; (*6*) Kryzhanovka; (*7*) Tiligul; (*8*) Tarkhankut; (*9*) Tizdar; (*10*) Nogaisk; (*11*) Port-Katon; (*12*) Shamin; (*13*) Chigirin; (*14*) Pivikha; (*15*) Gun'ki; (*16*) Priluki; (*17*) Gadyach; (*18*) Arapovichi; (*19*) Khotylevo; (*20*) Zapadnye Kairy; (*21*) Ushkalka; (*22*) Karai-Dubina; (*23*) Strelitsa; (*24*) Verkhnyaya Emancha; (*25*) Bogdanovka; (*26*) Uryv; (*27*) Veret'e; (*28*) Korotoyak; (*29*) Uspenka; (*30*) Klepki; (*31*) Il'inka; (*32*) Log Denisov; (*33*) Petropavlovka; (*34*) Novokhopersk; (*35*) Kuznetsovka; (*36*) Zherdevka; (*37*) Vol'naya Vershina; (*38*) Korostylevo; (*39*) Moiseevo; (*40*) Posevkino; (*41*) Perevoz; (*42*) Melik; (*43*) Rasskazovo; (*44*) Chekalin; (*45*) Alpat'evo; (*46*) Akkulaevo; (*47*) Cheremoshnik; (*48*) Chermenino; (*49*) Chulei; (*50*) Kipievo; (*51*) Akis'.

[1] We should emphasize that Topachevskii (1965) described the new lagurid form *Prolagurus praepannonicus* at the Nogaisk site. Subsequently, Rekovets (1994) showed that this form fits completely the intraspecific variability of *P. pannonicus* described from Hungary by Kormos. He considered *P. praepannonicus* as a synonym of the latter and transferred the more archaic subspecies *P. praepannonicus ternopolitanus* of Topachevskii into the rank of species *P. ternopolitanus*.

Voles from reference localities of Eastern Europe

Horizon	Localities	*Mimomys intermedius*	*M. pusillus*	*Clethrionomys sokolovi*	*Pliomys*	*Borsodia*	*Allophaiomys deucalion*	*Lagurodon arankae*	*Prolagurus ternopolitanus*	*Allophaiomys pliocaenicus*	*Eolagurus argyropuloi*	*Prolagurus pannonicus*	*Eolagurus simplicidens*	*Stenocranius hintoni*	*Clethrionomys glareolus*	*Pallasiinus protoeconomus*	*Microtus arvalinus*	*Microtus middendorffi-hyperboreus*	*Terricola arvaloides*	*Lagurus transiens*	*Stenocranius gregaloides*	*Pallasiinus oeconomus*	*Stenocranius gregalis*	*Eolagurus luteus*	*Dicrostonyx simplicior*	*Arvicola mosbachensis*	*Microtus arvalis*	*Lagurus lagurus*	*Dicrostonyx gulielmi-henseli*	*Arvicola terrestris*	*Dicrostonyx torquatus*
Holocene															•			•				•	•	•			•	•		•	•
Ostashkovo	Khotylevo 2																					•	•						•	•	
Monchalovo	Arapovichi																					•	•	•			•	•	•		
Kalinin	Gadyach																						•					•			
Mikulino	Cheremoshnik														•								•							•	
Moscow	Kipievo 2																						•						•		
	Chulei,																								•						
	Alpat'evo,																					•	•		•			•			
	Kipievo 1																					•			•						
Odintsovo	Strelitsa,														•				•			•	•	•		•	•				
	Verkhnyaya Emancha														•				•			•	•			•	•	•			
Dnieper	Akis'																					•			•						
	Chermenino																						•		•	•					
	Chekalin (u.b.)														•							•			•			•			
Likhvin	Pivikha														•				•	•		•	•	•		•	•				
	Priluki																			•			•								
	Gun'ki														•					•		•	•	•		•	•				
	Chigirin														•				•	•		•	•	•		•					
	Chekalin (m.b.)														•		•					•	•			•					
Oka	Chekalin (l.b.)														•							•	•		•						
Muchkap	Tiraspol' (Vorona)																						•	•							
	Vol'naya Vershina	•													•		•	•	•	•		•	•	•							
	Kuznetsovka,	•													•			•	•	•	•	•									
	Perevoz,																		•	•		•									
	Posevkino,																		•	•	•	•									
	Kolkotova Balka	•													•		•		•	•	•	•									
	Zherdevka,	•													•			•	•	•		•									
	Korotoyak 4	•													•		•	•	•	•	•	•									
Don	Bogdanovka	•													•	•		•		•	•										
	Moiseevo 3,														•	•		•		•	•										
	Klepki	•									•				•	•		•	•	•	•										
Il'inka	Novokhopersk 2	•	•										•	•		•	•	•		•											
	Moiseevo 2,		•										•		•			•		•											
	Korostylevo		•										•		•	•	•	•		•											
	Novokhopersk 1	•	•											•	•		•	•		•											
	Melik,												•		•	•	•	•		•											
	Veret'e,	•	•										•	•	•	•		•	•	•											
	Il'inka	•	•											•			•	•	•	•											

Table. (Contd.)

Horizon	Localities	*Mimomys intermedius*	*M. pusillus*	*Clethrionomys sokolovi*	*Pliomys*	*Borsodia*	*Allophaiomys deucalion*	*Lagurodon arankae*	*Prolagurus ternopolitanus*	*Allophaiomys pliocaenicus*	*Eolagurus argyropuloi*	*Prolagurus pannonicus*	*Eolagurus simplicidens*	*Stenocranius hintoni*	*Clethrionomys glareolus*	*Pallasiinus protoeconomus*	*Microtus arvalinus*	*Microtus middendorffi-hyperboreus*	*Terricola arvaloides*	*Lagurus transiens*	*Stenocranius gregaloides*	*Pallasiinus oeconomus*	*Stenocranius gregalis*	*Eolagurus luteus*	*Dicrostonyx simplicior*	*Arvicola mosbachensis*	*Microtus arvalis*	*Lagurus lagurus*	*Dicrostonyx gulielmi-henseli*	*Arvicola terrestris*	*Dicrostonyx torquatus*
Pokrovka	Uryv 3a	•	•								•	•		•		•		•	•											
Petropavlovka	Shamin	•									•			•		•	•													
	Petropavlovka,	•										•		•		•														
	Karai-Dubina	•									•	•		•	•	•														
Morozovka	Morozovka 1	•	•					•			•	•		•	•															
Nogaisk	Moiseevo 1									•		•																		
	Port-Katon	•	•	•						•		•																		
	Korotoyak 3c	•	•	•						•		•	•																	
	Zapadnye Kairy,	•		•						•	•	•																		
	Ushkalka,		•					•		•		•																		
	Roksolany	•						•		•		•																		
	Korotoyak 3b,	•	•		•					•	•	•																		
	Nogaisk	•		•				•		•		•																		
	Tarkhankut	•		•				•	•	•	•																			
	Korotoyak 3a								•	•			•																	
	Log Denisov	•		•					•	•																				
	Uspenka	•	•	•	•				•	•																				
	Akkulaevo (D + D)	•	•	•					•	•																				
Zhevakhova Gora	Chortkov,		•	•			•		•																					
	Zhevakhova Gora 5, 9	•		•			•	•	•																					
	Tizdar 2		•	•			•	•																						
	Kryzhanovka 4,			•		•	•																							
	Tizdar 1,		•			•	•																							
	Tiligul	•		•		•	•																							

Note: (l.b.), (m.b.), (u.b.) – lower, middle, and upper bone beds; (D + D) – the Davlekanovo and Dema horizons.

and Roksolany localities are close, though somewhat younger in age, as they reveal presence of more advanced of *Allophaiomys* morphotypes. In the magnetochronological scale, these localities should be placed below the Jaramillo Subchron, because the latter is recorded above the bone bed of the Roksolany locality (Dodonov *et al.*, 1998). The Korotoyak 3c locality that associates with the lower part of the Ostrogozhsk Formation lacking paleomagnetic characteristics (Iosifova *et al.*, 1992) can be placed near the lower boundary of the Jaramillo Subchron or just below it, because the upper part of the formation section shows the normally polarity and is correlated with the Jaramillo Subchron. The younger Port-Katon locality still localized within the Nogaisk Horizon can be placed above the Jaramillo Subchron, since the bone-bearing deposits reveal the reversed polarity. The somewhat younger Moiseevo 1 locality also should be assigned to the Nogaisk Hori-

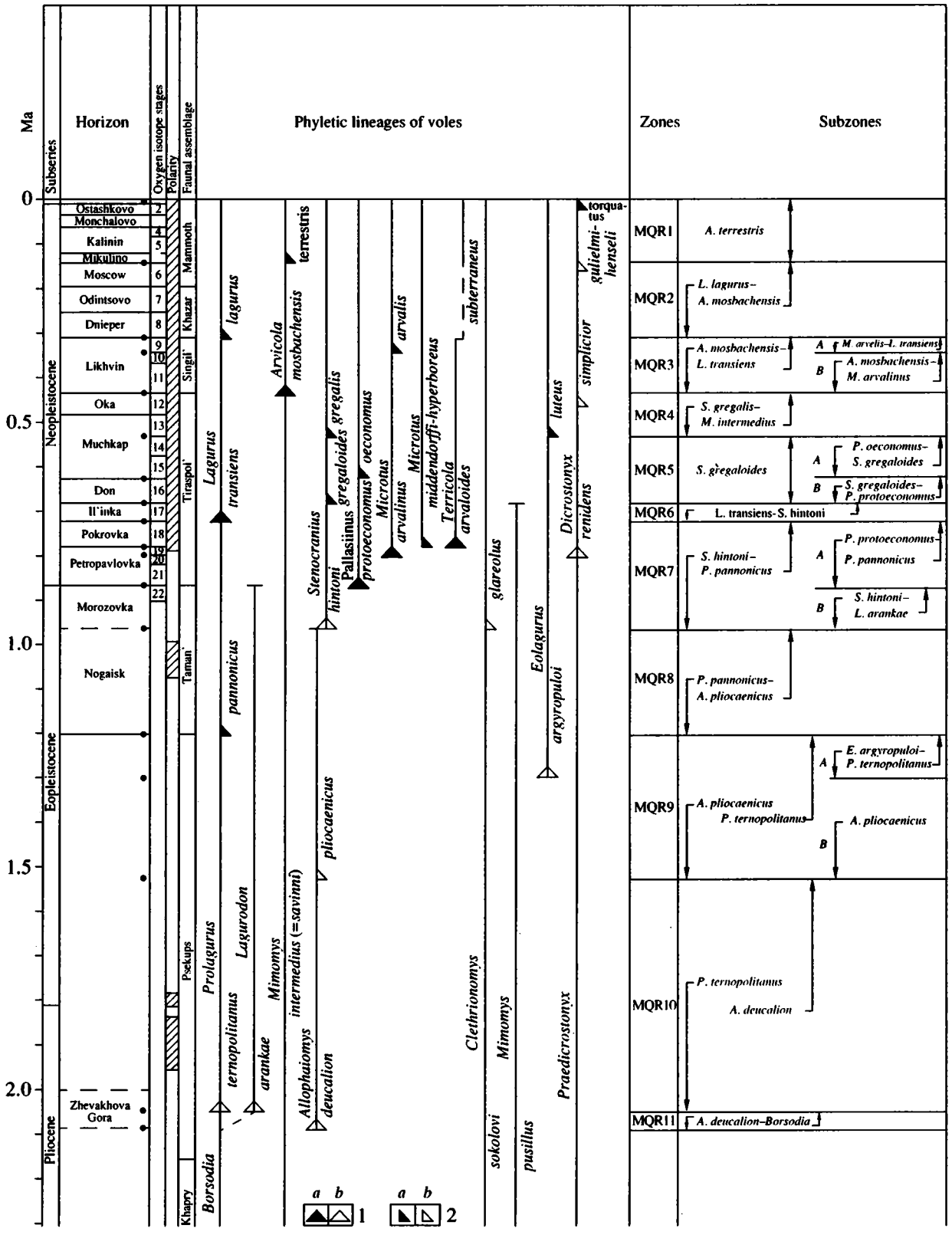

Fig. 2. Biozones and subzones of the Quaternary voles in Eastern Europe: (1) the appearance levels of vole genera related to the horizon boundaries (*a*), or of unknown precise position relative to horizons (*b*); (2) the appearance levels of new species related to horizon boundaries (*a*), or of unknown precise position relative to horizons (*b*).

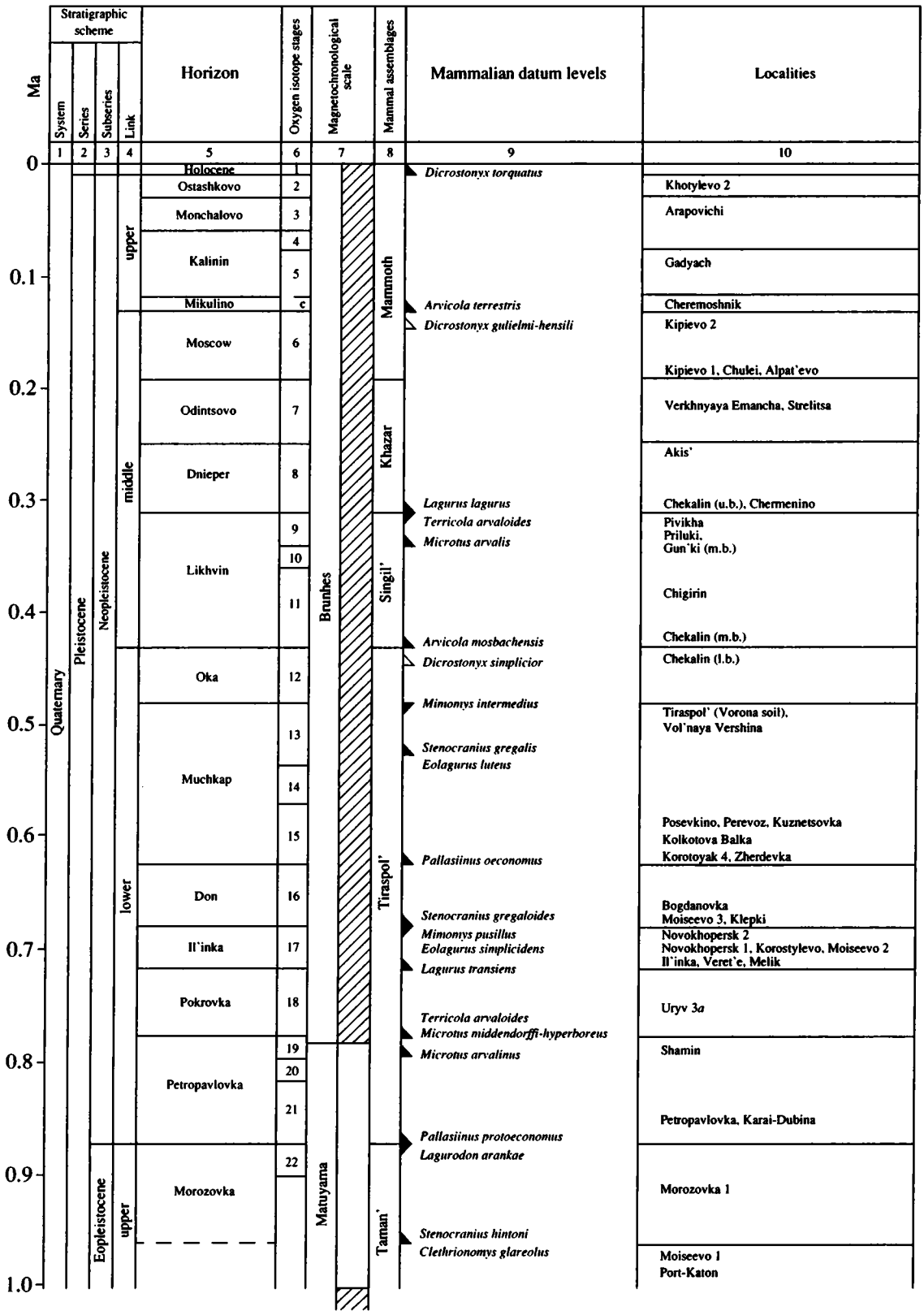

Fig. 3. Position of small mammal reference localities and datums in the magnetochronological and stratigraphic schemes: (1) the appearance levels of new species related to horizon boundaries (a), or of unknown precise position relative to horizons (b); (2) levels of species extinction. Letter symbols (l.b.), (m.b.), and (u.b.) denote lower, middle, and upper bone beds.

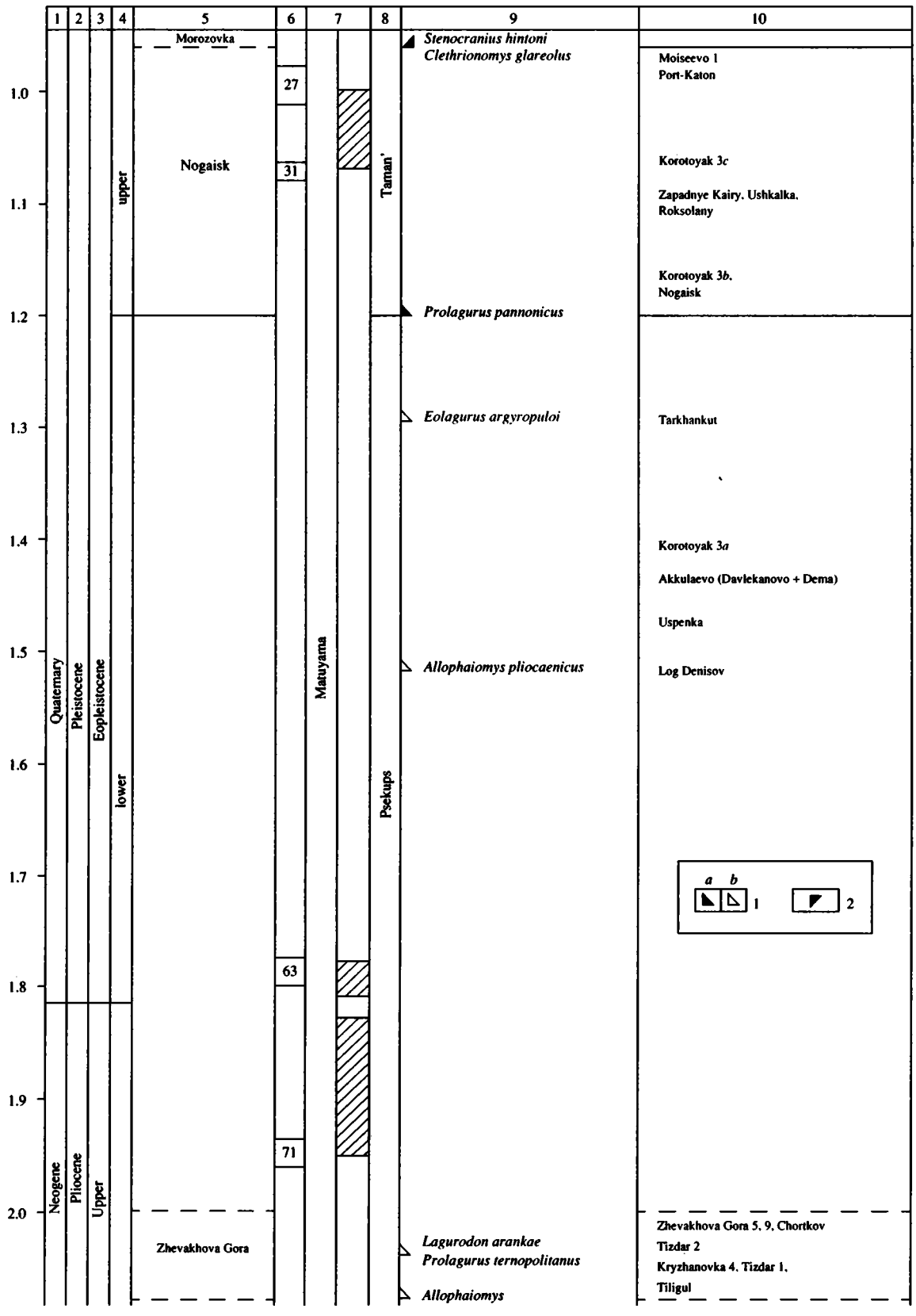
1
2
3
4
5
6
7
8
9
10
Morozovka
Nogaisk
Zhevakhova Gora
upper
lower
Quaternary
Pleistocene
Eopleistocene
Neogene
Pliocene
Upper
27
31
63
71
Matuyama
Taman'
Psekups
Stenocranius hintoni
Clethrionomys glareolus
Prolagurus pannonicus
Eolagurus argyropuloi
Allophaiomys pliocaenicus
Lagurodon arankae
Prolagurus ternopolitanus
Allophaiomys
Moiseevo 1
Port-Katon
Korotoyak 3c
Zapadnye Kairy, Ushkalka,
Roksolany
Korotoyak 3b,
Nogaisk
Tarkhankut
Korotoyak 3a
Akkulaevo (Davlekanovo + Dema)
Uspenka
Log Denisov
Zhevakhova Gora 5, 9, Chortkov
Tizdar 2
Kryzhanovka 4, Tizdar 1,
Tiligul
a
b
1
2
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

Fig. 3. (Contd.)

zon, because Agadzhanyan (see in *Verkhnii pliotsen...*, 1985) attributed here all vole remains of the *Allophaiomys–Stenocranius* lineage to the forms transitional between *Allophaiomys* and *"Pitymys" (= Stenocranius).*

The Morozovka 1 locality is the stratotype section of the Morozovka Horizon. It is characterized by the first occurrence of *Stenocranius hintoni* and *Clethrionomys glareolus.* The boundary between the Morozovka and overlying Petropavlovka horizons coincides with the lower boundary of the Neopleistocene in the general stratigraphic scheme of the Quaternary in Russia (resolution of the Interdepartmental Stratigraphic Commission, February 2, 1995) and with the boundary between the Taman' and Tiraspol' faunal assemblages. In the West European schemes, this level corresponds to the lower-middle Pleistocene boundary and to the Cromerian base that is correlated with the base of oxygen isotope stage 21. In such a case, the Matuyama-Brunhes inversion inside the oxygen isotope stage 19 (Shackleton, 1995) should be in the upper part of the Petropavlovka Horizon. This is exactly the case in the stratotype Petropavlovka section, where that inversion is recorded in the fossil soil developed on the Petropavlovka alluvium (*Verkhnii pliotsen...*, 1985).

The lower boundary of the Petropavlovka Horizon is marked by extinction of *Lagurodon arankae* and by first occurrence of *Microtus (Pallasiinus) protoeconomus.*[2] The Karai-Dubina locality and corresponding stratotype section are recognized in the lower part of the horizon. The Shamin locality in deposits of the reverse polarity is characterized by the first occurrence of *Microtus arvalinus* thus being slightly younger.

The lower boundary of the Pokrovka Horizon corresponds to the appearance level of *Microtus (Terricola) arvaloides* and *Microtus* ex gr. *middendorffi- hyperboreus* that are known from the Uryv 3a stratotype section. Deposits of the horizon are characterized by palynological spectra of the periglacial type and by occurrence of cold-resistant mollusks (*Opornye razrezy...*, 1984). These characteristics allow us to correlate the Pokrovka Horizon with the oxygen isotope stage 18.

The evolutionary level of voles from the Novokhopersk 1 and 2, Korostylevo, Moiseevo 2, Veret'e, and Melik localities is almost identical to that characterizing the Il'inka stratotype section. The mentioned localities are attributed to the Il'inka Horizon, the lower boundary of which is defined by the first occurrence of *Lagurus transiens.* Sediments of the horizon reveal presence of thermophilic mollusks and tortoise remains (Breslav *et al.*, 1992), according to which the Il'inka Horizon can be correlated with the warm stage 17. Faunas of the Bogdanovka, Moiseevo 3, and Klepki localities are close in composition to those from localities mentioned above. They are younger however and include *Stenocranius gregaloides* but lack *Mimomys pusillus* and *Eolagurus simplicidens* characteristic of more ancient faunas. Although the last localities occur below the Don moraine being referred by the majority of researchers to the Il'inka Horizon, we place them in the basal interval of the higher Don Horizon. This decision is based on the species composition that is somewhat impoverished as compared to that characterizing the preceding group of localities. Moreover, lemming bones occurring at the Bogdanovka site and abundant remains of *Microtus* ex gr. *middendorffi-hyperboreus* in all three localities indicate a comparatively cold climate during accumulation of burials. In addition, the deposits of the Moiseevo 3 and Klepki localities enclose pebbles of crystalline rocks that likely point to the onset of the Don glaciation (Udartsev *et al.*, 1979).

The lower boundary of the Muchkap Horizon is marked by the first occurrence of *Microtus (Pallasiinus) oeconomus* (Rekovets, 1994). In middle courses of the Don River, the Posevkino, Perevoz, Kuznetsovka, Korotoyak 4, and Zherdevka localities are referred to the lower part of the Muchkap Horizon. The two former are localized in the fossil soil of the Vorona pedocomplex immediately above moraine of the Don glacial tongue; and other sites are known in alluvial deposits also overlying this moraine. All the localities are characterized by the presence of *Stenocranius gregaloides* among shrub voles. We place the Kolkotova Balka site of the Dniester River region at the same stratigraphic level according to the fauna composition and evolutionary level of voles. The biometric age of elephants from the Kolkotova Balka locality is 590 ka (Vangengeim and Pevzner, 2000), and this, along with absence cold-resistant taxa, permit the correlation of the site with the oxygen isotope stage 15. Accordingly, the lower part of the Muchkap Horizon corresponds to the same stage 15, and the Don Horizon cannot be younger than the stage 16.

The Vol'naya Vershina locality, the Muchkap Horizon stratotype, and the Tiraspol' site (the Vorona soil) are obviously younger than the previous group of localities, because *Stenocranius gregaloides* is replaced in this case by more advanced *S. gregalis. Eolagurus luteus* appears at the same level instead of *E. argiropuloi.* The molluscan assemblage of the Muchkap Horizon stratotype suggests origin under warm climatic conditions, and we correlate the horizon with the oxygen isotope stage 13.

The lower fluvioglacial sediments left by of the Oka glaciation at the Chekalin locality are referred to the Oka Horizon and correlated with the oxygen isotope stage 12.

[2] The early form of the *Microtus (Pallasiinus)* lineage usually known in Russian publications as *M.* ex gr. (cf.) *oeconomus* was distinguished by Rekovets (1994) as the particular species *M. protoeconomus.*

We consider the Likhvin Horizon in a wide range of 11 to 9 stages of the oxygen isotopic scale. The corresponding fauna is known as the Singil' assemblage. *Arvicola mosbachensis (= A. cantianus)* appeared at the base of the horizon, whereas the upper boundary of the latter is marked by appearance of *Lagurus lagurus* and by extinction of *Terricola arvaloides. Mimomys intermedius*, the direct ancestor of *Arvicola*, is unknown in faunas younger than the uppermost Muchkap Horizon. The middle lacustrine lens (stratotype of the Likhvin interglacial) at the Chekalin locality is referred to the lowermost part of the Likhvin Horizon and to the oxygen isotope stage 11. The Chigirin fauna is close in age. The group of younger localities is known from the upper part of the Likhvin Horizon. According to succession of *Lagurus lagurus* and *L. transiens* morphotypes, these localities can be arranged in the following order according to the age decrease: the Gun'ki (middle bed), Priluki, and Pivikha sites. *Microtus arvalis* appeared first in the Gun'ki site.[3] The spore and pollen assemblages point to a warm climate in the corresponding period (Markova, 1982), and we place the indicated localities at the level of oxygen isotope stage 9.

The upper fluvioglacial bed of the Chekalin locality and alluvial sediments of the Chermenino site, where they underlie the Dnieper moraine second from the top, are referred to the lowermost part of the Dnieper Horizon. Judging from the evolutionary advancement of *Dicrostonyx* forms, the localities are of the same age (*Razrezy otlozhenii...*, 1977; Agadzhanyan, 1976).

At the Akis' locality, deposits that overlie the second moraine from the top are attributed to the upper portion of the Dnieper Horizon. The comparative morphology of *Dicrostonyx* teeth shows that this locality is somewhat younger than the upper bone bed at the Chekalin site (Guslitser and Isaichev, 1983). *Arvicola* forms of the Verkhnyaya Emancha and Strelitsa sites are of a similar evolutionary level but more advanced as compared to *Arvicola* species from the Gun'ki and Pivikha localities. The molluscan fauna from the Strelitsa site suggests a warm climate during its lifetime, and we feel it possible to attribute the Verkhnyaya Emancha and Strelitsa localities to the Odintsovo Horizon and to correlate the latter with the oxygen isotope stage 7.

Sediments underlying the upper moraine at the Kipievo 1 and Chulei sites, are referred to the lower part of the Moscow Horizon. According to the relationship of *Dicrostonyx* morphotypes, the Alpat'evo locality is close in age to them (Markova, 1982). Deposits overlying the upper moraine at the Kipievo 2 locality are correlated with upper strata the Moscow Horizon, as lemmings are represented here by the more advanced *Dicrostonyx* ex gr. *gulielmi-henseli.*

The lower boundary of the Mikulino Horizon is determined by the appearance of *Arvicola terrestris.* The Cheremoshnik locality, where the mammalian fauna was collected from the Mikulino peat deposits (Agadzhanyan, 1972), is attributed to this horizon. The majority of researchers correlates the Mikulino interglacial with the oxygen isotope stage 5e, placing the Dnieper and Moscow horizons at the levels of stages 8 and 6, respectively.

The Gadyach locality of the steppe mammalian fauna is referred to the Kalinin Horizon. The Arapovichi locality in the Bryansk soil yields *Dicrostonyx* ex gr. *gulielmi-henseli* and is placed in the Monchalovo Horizon corresponding to the oxygen isotope stage 3. The Khotylevo 2 locality of 23600 ± 270 years old according to ^{14}C date (Markova, 1982) is attributed to the Ostashkovo Horizon. At this site, lemmings are still represented by *D. gulielmi-henseli*, whereas the more advanced *D. torquatus* is known from numerous localities of the Holocene age (*Stratigrafiya SSSR...*, 1982).

REGIONAL MAMMAL ZONES OF EASTERN EUROPE

Eleven range and concurrent range zones of vole species were distinguished within the analyzed time range (Fig. 2). The zones are characterized below from the basal one upward.

MQR 11: the *Allophaiomys deucalion-Borsodia* concurrent range zone with the base determined by the first appearance datum (FAD) of the genus *Allophaiomys*; the FAD of the genera *Lagurodon* and *Prolagurus* define its upper limit.

Characteristic taxa are *Allophaiomys deucalion, Mimomys intermedius (= M. savini), M. pusillus*, advanced forms of *Borsodia*, and archaic *Clethrionomys.*

Type locality: Tizdar 1, and **other localities** are Tiligul and Kryzhanovka 4.

Ages of lower and upper boundaries cannot be established precisely. Both boundaries are older than the Olduvai Subchron.

MQR 10: the *Prolagurus ternopolitanus–Allophaiomys deucalion* concurrent range zone, the lower boundary of which corresponds to the FAD *Prolagurus* genus, and the upper one to the last appearance datum (LAD) of *Allophaiomys deucalion.*

Characteristic taxa are *Allophaiomys deucalion, Lagurodon arankae, Prolagurus ternopolitanus, Mimomys intermedius, M. pusillus*, and archaic *Clethrionomys.*

Type locality is Zhevakhova Gora 5 and 9. **Other localities** are Tizdar 2 and Chortkov.

The age of upper boundary is not established. The boundary is somewhat above the Olduvai Subchron.

[3] In opinion of Rekovets (1994), this form having index values of AL > 55 and d/e < 25 differs from ancestral *M. arvalinus.*

MQR 9: the *Allophaiomys pliocaenicus–Prolagurus ternopolitanus* concurrent range zone; its lower boundary corresponds to the FAD of *Allophaiomys pliocaenicus*, and the top to the LAD of *Prolagurus ternopolitanus*.

Characteristic taxa are *Allophaiomys pliocaenicus, Prolagurus ternopolitanus, Lagurodon arankae, Mimomys intermedius*, and *M. pusillus*. The first appearance of *Eolagurus argiropuloi* is recorded in the upper part of the zone.

Type locality is Uspenka. **Other localities** are Akkulaevo (the Dema and Davlekanovo horizons), Log Denisov, Korotoyak 3a, and Tarkhankut.

The age of the upper boundary is 1.2 Ma. This datum coincides with the boundary between the Psekups and Taman' faunal assemblages and with the base of the Nogaisk Horizon.

The zone is subdivided into two **subzones.** The lower *Allophaiomys pliocaenicus* subzone (**MQR 9B**) spans the interval from the *A. pliocaenicus* FAD to the *Eolagurus argiropuloi* FAD. The upper subordinate unit **MQR 9A** is defined as the *Eolagurus argiropuloi–Prolagurus ternopolitanus* concurrent range subzone. Its interval is between the *E. argiropuloi* FAD and the *P. ternopolitanus* LAD.

MQR 8: the *Prolagurus pannonicus–Allophaiomys pliocaenicus* concurrent range zone with the lower boundary defined by the FAD of *Prolagurus pannonicus*; the upper boundary is marked by extinction of the genus *Allophaiomys*.

Characteristic taxa are *Allophaiomys pliocaenicus, Prolagurus pannonicus, Lagurodon arankae, Mimomys intermedius, M. pusillus*, and *Clethrionomys sokolovi*.

Type locality is Nogaisk. **Other localities** are Korotoyak 3b, c, Roksolany, Ushkalka, Zapadnye Kairy, Port-Katon, and Moiseevo 1.

The zone corresponds to the Nogaisk Horizon. The age of the upper boundary is slightly younger than the Jaramillo Subchron.

MQR 7: the *Stenocranius hintoni–Prolagurus pannonicus* concurrent range zone, the base of which is placed at the FAD of *Stenocranius hintoni*; the top corresponds to the LAD of *Prolagurus pannonicus*. At the lower boundary of the unit, *Clethrionomys sokolovi* is replaced by *C. glareolus*.

Characteristic taxa are *Stenocranius hintoni, Prolagurus pannonicus*, and *Mimomys intermedius*. Abundance of *M. pusillus* decreases. The extinction of *Lagurodon* and the FAD of *Pallasiinus protoeconomus* are recorded in the lower part of the zone. *Microtus arvalinus, Terricola arvaloides*, and *Microtus* ex gr. *middendorffi-hyperboreus* appeared in the upper part of the zone.

Type locality is Karai-Dubina. **Other localities** are Morozovka 1, Petropavlovka, Shamin, and Uryv 3a.

The upper limit corresponds to the boundary between the oxygen isotope stages 18 and 17, i.e., to about 715 ka. The Matuyama-Brunhes inversion is recorded in the upper part of the unit.

The zone is subdivided into two subzones. The lower concurrent range subzone of *Stenocranius hintoni* and *Lagurodon arankae* is designated as **MQR 7B** and ranges from the *S. hintoni* FAD to the extinction level of *Lagurodon*. The subzone corresponds to the Morozovka Horizon. Its top coincides with the boundary that separates the Taman' and Tiraspol' faunal assemblages, and also the oxygen isotope stages 22 and 21; the boundary age corresponds to ca. 865 ka. The upper unit **MQR 7A** or the *Pallasiinus protoeconomus–Prolagurus pannonicus* concurrent range subzone is identified between the *P. protoeconomus* FAD and the *Prolagurus pannonicus* LAD. The subzone is correlative with the Petropavlovka and Pokrovka horizons.

MQR 6: the *Lagurus transiens–Stenocranius hintoni* concurrent range zone; its lower and upper boundaries are defined by the *L. transiens* FAD and the *S. hintoni* LAD, respectively.

Characteristic taxa are *Mimomys intermedius, Lagurus transiens, Stenocranius hintoni, Pallasiinus protoeconomus, Microtus* ex gr. *middendorffi-hyperboreus*, and *M. arvalinus* associated with last *Mimomys pusillus* and *Eolagurus simplicidens*.

Type locality is Il'inka. **Other localities** are Veret'e, Melik, Novokhopersk 1, 2, Korostylevo, and Moiseevo 2.

The zone corresponds to the Il'inka Horizon and to the oxygen isotope stage 17. The upper boundary **age** is about 680 ka.

MQR 5: the *Stenocranius gregaloides* total range zone; its top is marked by first appearance of *Eolagurus luteus*.

Characteristic taxa are *Lagurus transiens, Stenocranius gregaloides, Clethrionomys glareolus, Microtus arvalinus, and Microtus* ex gr. *middendorffi-hyperboreus*. The genus *Mimomys* is represented by *M. intermedius* only. Species *Terricola arvaloides* are abundant. *Pallasiinus protoeconomus* appears in the lower part of the zone to be subsequently replaced by *P. oeconomus* in the upper part.

Type locality is Kolkotova Balka. **Other localities** are Klepki, Moiseevo 3, Bogdanovka, Korotoyak 4, Zherdevka, Posevkino, Perevoz, and Kuznetsovka.

The upper boundary is inside the Muchkap Horizon and coincides with the base of the oxygen isotope stage 13 dated back to 530 ka.

Two **subzones** distinguished within the unit are separated by the boundary that marks the evolutionary transition from *Pallasiinus protoeconomus* to *P. oeconomus*. The boundary coincides with basal levels of the Muchkap Horizon and the oxygen isotope stage 15 (about 625 ka). The lower subdivision **MQR 5B** or

the *Stenocranius gregaloides–Pallasiinus protoeconomus* concurrent range subzone is correlative to the oxygen isotope stage 16. The upper *Pallasiinus oeconomus–Stenocranius gregaloides* concurrent range subzone (**MQR 5A**) spans the interval of stages 14 and 15.

MQR 4: the *Stenocranius gregalis–Mimomys intermedius* concurrent range zone; the unit is bounded by the *Stenocranius gregalis* FAD at the base and by the extinction level of the genus *Mimomys* at the top.

Characteristic taxa are *Stenocranius gregalis, Eolagurus luteus, Clethrionomys glareolus, Microtus* ex gr. *middendorffi-hyperboreus, Terricola arvaloides,* and *Pallasiinus oeconomus.*

Type locality is Vol'naya Vershina. **Other localities** are Tiraspol' (upper bed, the Vorona soil) and Chekalin (lower bed).

The top of the zone coincides with the boundary that separates the Tiraspol' and Singil' faunal assemblages and the Oka and Likhvin horizons. This level corresponds to the base of the oxygen isotope stage 11 and is about 430 ka old. It should be noted here that the extinction time of *Mimomys* forms is not determined with precision. Neither *Mimomys intermedius* nor its direct descendant *Arvicola mosbachensis* are known from the Oka Horizon. Accordingly, the time of the *Mimomys–Arvicola* transition is unclear. This event could take place at any level of the Oka Horizon.

MQR 3: the *Arvicola mosbachensis-Lagurus transiens* concurrent range zone with the lower boundary defined by the *Arvicola mosbachensis* FAD; its upper limit corresponds to the *Lagurus transiens* LAD.

Characteristic taxa are *Arvicola mosbachensis, Lagurus transiens, Clethrionomys glareolus, Stenocranius gregalis,* and *Pallasiinus oeconomus* associated with *Microtus arvalis* in the upper part of the zone.

Type locality is Chigirin. **Other localities** are Chekalin (middle bed), Gun'ki, Priluki, and Pivikha.

The zone corresponds to the ranges of the Likhvin Horizon and Singil' faunal assemblage, and also to the summary interval of 11 to 9 oxygen isotope stages. The upper boundary is dated back to ca. 310 ka.

The zone is subdivided into two **subzones. MQR 3B** or the lower *Arvicola mosbachensis–Microtus arvalinus* concurrent range subzone has upper boundary corresponding to the transition from *Microtus arvalinus* to *Microtus arvalis* and to the base of the oxygen isotope stage 9 at the level of about 340 ka. The upper *Microtus arvalis–Lagurus transiens* concurrent range subzone (**MQR 3A**) is correlative to the stage 9.

MQR 2: the *Lagurus lagurus–Arvicola mosbachensis* concurrent range zone with the *Lagurus lagurus* FAD at the base and the *Arvicola mosbachensis* LAD at the top.

Characteristic taxa are *Lagurus lagurus, Arvicola mosbachensis, Stenocranius gregalis, Pallasiinis oeconomus,* and *Dicrostonyx simplicior* that is succeeded by *D.* ex gr. *gulielmi-henseli* in the uppermost part of the zone.

Type locality is Alpat'evo. **Other localities** are Chekalin (the upper bed), Chermenino, Akis', Kipievo 1, 2, Chulei, Verkhnyaya Emancha, and Strelitsa.

The zone corresponds to the three horizons distinguished in the second half of the middle Neopleistocene. **The age** of the upper boundary is about 135 ka (the base of the oxygen isotope stage 5).

MQR 1: the *Arvicola terrestris* total range zone.

Characteristic taxa are *Arvicola terrestris* and *Dicrostonyx* ex gr. *gulielmi-henseli,* the latter replaced by *D. torquatus* across the lower Holocene boundary. Other voles are represented by modern species.

Type locality is Khotylevo 2. **Other localities** are Cheremoshnik, Gadyach, and Arapovichi.

The zone corresponds to the summary range of the upper Neopleistocene and Holocene.

CONCLUSION

The proposed biostratigraphic zonation of Quaternary small mammals is much more detailed than the subdivision scheme based on faunal assemblages distinguished by Gromov. In particular, the Psekups faunal assemblage corresponds to two zones and two subzones, the Taman' assemblage to a zone and subzone, the Tiraspol' fauna to two zones and three subzones, and the Singil' assemblage to two subzones. The Neopleistocene subdivisions are most detailed. Their time ranges are from 30 to 75 thousands years. At the current state of knowledge, the distinguished Eopleistocene subdivisions are less detailed. Their mean duration is about 270 thousands years.

The presently accepted datums that separate zonal units may be changed subsequently, when stratigraphic positions of reference localities will be refined and more precisely correlated with the oxygen isotope stages, or when the stage ages proper will be revised, etc. However, regardless the possible changeability of the stratigraphic and zonal boundary ages, the succession of distinguished zones will be invariable, as it depicts the directional and irreversible evolution of mammals. This is the major advantage of stratigraphic subdivisions based on distribution mammal remains as compared to those obtained with the help of climatostratigraphic methods, because the identical climatic situations may repeate with time.

In our opinion, basic objectives of future investigations could be formulated as follows: (1) the more detailed subdivision of the Eopleistocene (necessary prerequisites are known); (2) the understanding of spatial continuation of the distinguished zones in the northern Palearctic; (3) the refinement of zonal boundary ages; and (4) the recognition and thorough examination of new phyletic lineages, which may be used for a more detailed subdivision.

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Fission-Track Dating of Detrital Zircons from Sandstone of the Lesnaya Group, Northern Kamchatka

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Abstract—Flyschoid deposits of the Lesnaya Group that are exposed within northern Kamchatka are almost barren of identifiable fossils. The group is considered to be of the Late Cretaceous age on the basis of geological correlation. Ages of detrital zircons from nine sandstone samples of the Lesnaya Group are determined using the fission-track dating. The youngest population of colorless idiomorphic zircon crystals, which experienced no secondary annealing, is from 43.7 ± 3.4 to 58.1 ± 4.2 Ma old. Morphological features of zircons allow us to relate their formation to the volcanic activity synchronous to accumulation of the Lesnaya Group flysch. Hypabyssal intrusions and blocks of older rocks that experienced rapid exhumation from the depth, where thermal parameters exceeded the blocking temperature, could be the source rocks for younger zircons. The age of the youngest zircon population can be interpreted as corresponding to sedimentation time of the Lesnaya Group that lasted, according to our data, until the mid-Middle Eocene.

Key words: *fission-track dating, detrital thermochronology, zircon, Lesnaya Group, northern Kamchatka.*

INTRODUCTION

The dating of flyschoid deposits in Boreal provinces, which contain almost unidentifiable organic remains, is a difficult problem of geochronology and stratigraphy. Some papers published in western countries during the past decade demonstrated that the problem could be solved with the help of the detrital thermochronology based on the fission-track dating of zircon and apatite grains from sedimentary rocks. The method is shown to be useful for establishing ages of those deposits, dating of which on the basis of paleontological remains is highly conjectural.

In our study, we applied the detrital thermochronology for elucidating the deposition period of the flyschoid Lesnaya Group constituting the core of the Lesnaya Upland in northern Kamchatka.

LESNAYA GROUP: BRIEF DESCRIPTION

The Lesnaya Group is distinguished in western slopes of the Sredinnyi Range of the Kamchatka Isthmus (Fig. 1). It is composed of sandy–clayey flyschoid sediments deposited along the continental slope of Eurasia and occurring now as the autochthonous Lesnaya thrust sheet intensely dislocated and overridden by the siliceous–volcanogenic Irunei unit related in origin to the Olyutorskii island arc (Santonian–Maastrichtian, probably Danian) (*Geologicheskaya karta...*, 1989; Shantser *et al.*, 1985; Fedorchuk and Izvekov, 1992). Immediately below the Lesnaya thrust fault, the group includes exotic blocks of siliceous–volcanogenic deposits that yield impoverished assemblages of Campanian–Maastrichtian radiolarians (Shapiro and Fedorov, 1985). Origin of those blocks is debatable.

Considerable deformations and the uniform composition of sediments lacking macrofauna are unfavorable for the correct interpretation of rock succession, and inferences on their age are mainly based on dates obtained for some localities and on the correlation with lithologically similar deposits occupying an analogous structural position in other parts of the region. In particular, there were found some Santonian–Campanian inocerams and Maastrichtian–Danian assemblages of agglutinated benthic foraminifers (*Geologicheskaya karta...*, 1989). Fedorchuk and Izvekov (1992) reported in addition on some occurrences of the Late Cretaceous and Eocene nannoplankton in mudstone beds of the Lesnaya Group. The group correlates with an upper part of the Cretaceous Omgon Group in the western coast of Kamchatka (*Geologicheskaya karta...*, 1989), with the Khozgon Formation of the southern Sredinnyi Ridge that yields Campanian radiolarians (Shapiro *et al.*, 1986), and with the Ukelayat flysch of the southern Koryak Upland, where its stratigraphic range is thought to be spanning the Upper Cretaceous, Paleocene, and basal Eocene (Ermakov and Suprunenko, 1975; Bogdanov *et al.*, 1987; Garver *et al.*, 1998; Solov'ev *et al.*, 1998). The Lesnaya Group is assigned to the Upper Cretaceous in the geological maps available.

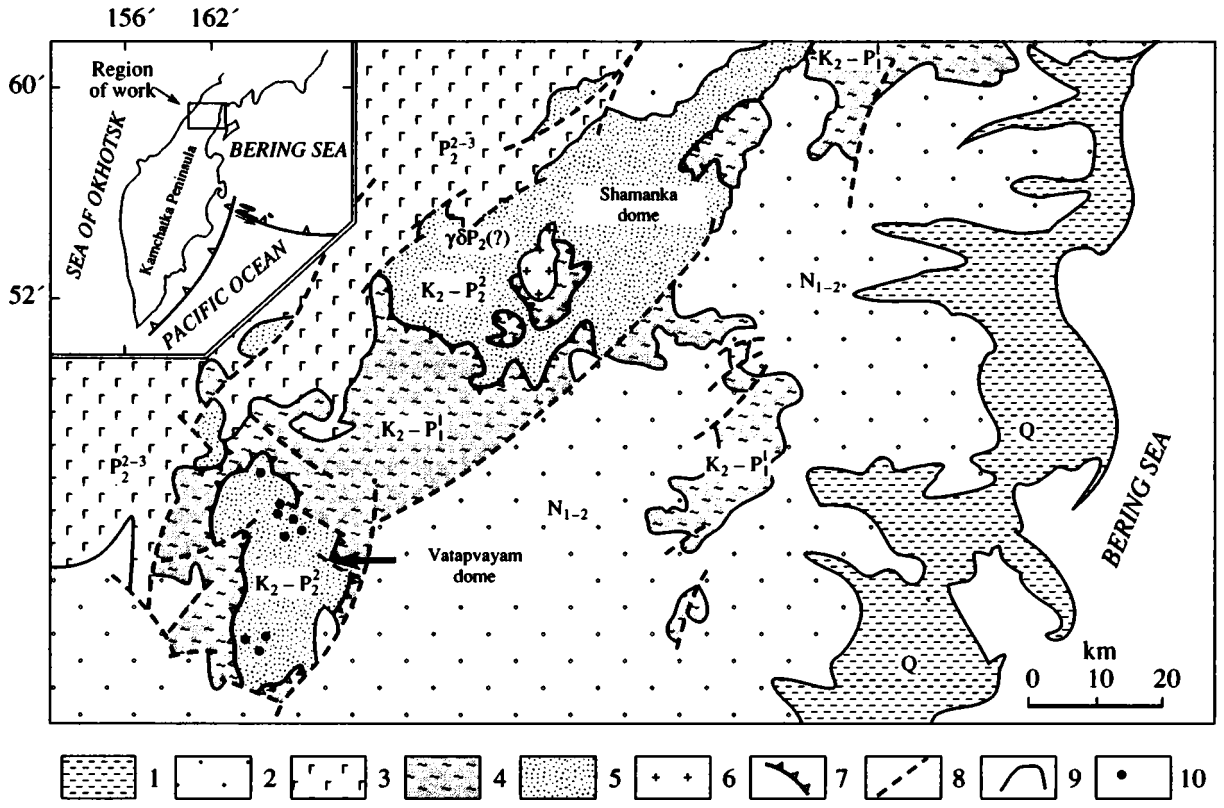

Fig. 1. Simplified geological structure of the study area (*Geologicheskaya karta...*, 1989, with modifications): (1) Quaternary deposits; (2) Central Kamchatka volcanic belt (N_{1-2}); (3) Western Kamchatka volcanic belt (P_2^{2-3}); (4) exposures of the Irunei Formation (K_2-P_1^1); (5) exposures of the Lesnaya Group (K_2-P_2^2); (6) Shamanka Massif of the Middle Eocene granite; (7) Lesnaya thrust fault; (8) other faults; (9) stratigraphic contacts; (10) sampling sites.

The upper age limit of the Lesnaya Group is inferable from the age of the neoautochthon composed of unconformably lying terrestrial volcanics of the Kinkil Formation that is attributed to the Middle Eocene on the basis of K/Ar dates ranging from 37 to 47 Ma (Gladenkov *et al.*, 1991). In upper reaches of the Shamanka River, conglomerates of the Upper Eocene contain pebbles of granite intruding the Lesnaya Group, Irunei Formation, and thrust fault separating them (Shantser *et al.*, 1985).

Data on the Lesnaya Group age are controversial but very important for the analysis of the regional geology. In this connection, we dated detrital zircon from the Lesnaya Group sandstones.

PRINCIPLES OF DETRITAL THERMOCHRONOLOGY

At the beginning of the 1960s, American researchers suggested a new method of the mineral age determination based on the density calculation of fission-tracks originated by spontaneous decay ^{238}U nuclei during the geological history of a mineral (Price and Walker, 1963; Fleischer, Price, and Walker, 1975). In Russia, the method was termed as the dating based on tracks of the uranium nuclear debris (Shukolyukov *et al.*, 1965). In this work, we use the original term "fission-track dating".

The development of fission tracks in a mineral can be compared with the accumulation process of radiogenic isotopes in the course of radioactive decay. The annealing (disappearance) of tracks in most minerals happens at the temperature of more than 300°C, i.e., the tracks appear and survive in crystals only if the rock is cooled below a particular temperature called "the closure temperature". The closure temperature is different in various minerals, and this allows the fission-track dating to be applied for studying thermal events related to orogeny and volcanism in active geodynamic settings of the Earth. The fission-track ages of zircon and apatite are most frequently used for solving geological problems (Wagner and Van den Haute, 1992).

We used the detrital thermochronology in our work, as it offers a chance to establish the cooling time of rocks in provenances, which supplied sedimentary sequences with detrital minerals (Hurford *et al.*, 1984; Baldwin *et al.*, 1986; Brandon and Vance, 1992; Garver

and Brandon, 1994; Carter *et al.*, 1995). The cooling of rocks in a provenance can be associated with different geological processes, e.g., with the exhumation of rocks from a large depth or with volcanic activity; the redeposition of older sediments is also a possibility. In the works mentioned above, the fission-track age of individual detrital zircons was determined in order to distinguish subsequently their populations (Galbrain and Green, 1990; Brandon, 1992; Brandon, 1996) that arrived in the sedimentary basin from different provenances and had different ages. As was shown, the fission-track age of detrital zircons that escaped a secondary annealing, could be used for establishing the age of terrigenous sedimentation. The youngest population of zircon grains defines the age of sedimentation, when the latter was synchronous to volcanism that developed in immediate vicinity of the sedimentation site (Brandon and Vance, 1992; Garver and Brandon, 1994). In particular, the youngest zircon population marks the lower time limit of the sedimentation cessation, and this is very important for the analysis of accumulation history of the Lesnaya Group and geodynamics of Kamchatka at the Mesozoic–Cenozoic boundary.

AGE OF ZIRCONS FROM SANDSTONES OF THE LESNAYA GROUP

We selected nine sandstone samples (each 4–8 kg in weight) of the Lesnaya Group within the area of the Vatapvayam dome: three samples in the southwestern part (Mt. Gechanana) and six samples in the northeastern part (the northern slope of the Levaya Lesnaya River valley) of the latter (Fig. 1). Zircons were extracted from sandstone at the Laboratory of Accessory Minerals, the Institute of the Lithosphere of Marginal Seas, Russian Academy of Sciences. The zircon ages were measured at the Laboratory of Fission-Track Dating, the Union College (Schenectady, NY, USA). The method of an external detector was applied when dating (Hurford and Carter, 1991). Peculiarities of the technical treatment of samples to be dated are characterized in notes to Table 2.

From 45 to 90 zircon grains from each sample were dated (Table 2). Presented as an example are calculation data and ages for individual zircon grains from Sample L10 (Table 1). The program "Zetaage 4.7" by M.T. Brandon (Yale University, USA) was applied for calculating the age of zircon grains. The program is available for any user at the site http:\\love.geology.yale.edu/~brandon.

Ages of zircon grains vary within a wide range in all samples (for instance, Sample L10 in Table 1, Fig. 2b), thus suggesting that zircons arrived to the basin of sedimentation from different provenances, and that we deal with several zircon populations different in age. To separate different populations, we applied the method described earlier (Galbraith and Green, 1990; Brandon, 1992; Brandon, 1996). According to this method, the measured ages of individual grains characterize several zircon populations (this is correct, as the studied zircons are of different morphology), and distribution of ages in each population obeys the same model law. We used the binomial approximation in our study. The model parameters and, in particular, the position of distribution peaks for individual populations is assessed using the maximum-likelihood method. The number of populations is chosen according to the error minimization criterion (criterion 2) for the assessed parameters. To separate populations of different age in our study, we applied the program Binomfit 1.8 by Brandon (Yale University, USA) that uses the algorithm by Galbrain (1988). The program is available for any user at the site http:\\love.geology.yale.edu/~brandon.

The results of subdividing populations of zircon grain from nine samples are given in Table 2 (Fig. 2a, b, c). Two populations were selected from samples L1 and L13, and three populations from the others. These groups of populations (peaks in Fig. 2a, b, c) minimize errors of assessed parameters best of all, whereas smaller or greater amounts of "peaks" used on calculations considerably deteriorate the result. It should be pointed out that the peak "width" (W) that characterizes the relative standard deviation varies from 19 to 29% proving the result validity (Brandon, 1996).

Thus, the analysis of distribution of fission-track ages measured for nine rock samples revealed three zircon populations of different age: (P1) 44–58 Ma, (P2) 71–93 Ma, and (P3) 104–176 Ma (Table 2).

As the individual zircon grains from each sample show widely variable ages (Fig. 2a, b, c), we can assume that they, when arrived in the basin, have never been heated up to or above the temperature (about 215–240°C) able to cause the track system closure (Brandon and Vance, 1992). Consequently, these zircons characterize the time range of rock cooling in provenances.

Zircons of the youngest population are mainly represented by colorless idiomorphic crystals. This morphological feature allows a suggestion that zircons of this kind formed during the volcanic activity synchronous to accumulation of the Lesnaya Group, and appeared in the basin of sedimentation shortly after their formation. Accordingly, the youngest zircon population is interpreted as characterizing the accumulation period of the Lesnaya Group that lasted (see Fig. 2d) from the latest Paleocene (58.1 ± 4.2 Ma) to the mid-Middle Eocene (43.7 ± 3.4).

Zircons from older populations are more diverse in morphology. Smoothed crystal fragments dominate among them, whereas rounded grains and idiomorphic crystals are rare. Zircons of these populations (P2, P3, Table 2) have been likely derived from other provenances and characterize the cooling history of parental rocks under impact of different geological processes (Garver *et al.*, in press). It is likely that their provenances were in the Okhotsk-Chukchi volcano-plutonic belt originated above the different-age terranes. It is

Table 1. Calculated parameters of fission tracks in zircon grains, Sample L10. First plate L10a, etching time 15 hours (see notes for Table 2)

Grain number	ρs	Ns	ρi	Ni	Area	U ± 2se		Grain age	Age* ±95%
1	5.44	45	4.48	37	12	133	44	75.2	47.5–119.7
2	6.00	62	4.26	44	15	127	39	87.0	58.1–131.4
3	4.90	54	6.17	68	16	184	46	49.3	33.7–71.7
4	5.42	56	5.71	59	15	170	45	58.8	39.9–86.5
5	5.81	44	5.15	39	11	153	50	69.8	44.2–110.5
6	9.51	59	9.51	59	9	284	76	61.9	42.3–90.7
7	5.66	78	8.71	120	20	260	50	40.2	30.0–53.8
8	4.84	40	4.48	37	12	133	44	66.9	41.6–107.7
9	4.72	39	4.84	40	12	144	46	60.4	37.8–96.5
10	11.6	64	17.8	98	8	530	111	40.6	29.0–56.4
11	7.50	62	7.14	59	12	213	57	65.1	44.7–94.8
12	7.74	48	4.52	28	9	135	51	105.6	65.0–174.9
13	8.22	34	7.26	30	6	216	79	70.1	41.6–118.7
14	4.45	46	3.58	37	15	107	35	76.9	48.7–122.0
15	10.7	118	6.44	71	16	192	47	102.5	75.5–140.2
16	5.56	69	8.87	110	18	265	53	39.0	28.2–53.3
17	10.1	104	6.58	68	15	196	49	94.4	68.7–130.6
18	6.05	50	4.23	35	12	126	43	88.2	56.1–140.2
19	4.96	41	3.14	26	12	94	37	97.2	58.1–165.6
20	11.4	94	7.62	63	12	227	59	92.1	66.1–129.3
21	6.17	51	6.17	51	12	184	52	61.9	41.1–93.4
22	10.1	111	6.89	76	16	206	49	90.2	66.5–122.9
23	9.92	82	12.9	107	12	386	78	47.6	35.0–64.3
24	9.19	95	7.06	73	15	211	51	80.5	58.5–111.1
25	6.33	109	7.14	123	25	213	40	54.7	41.9–71.4
26	8.03	166	7.50	155	30	224	38	66.1	52.5–83.1
27	6.53	72	5.26	58	16	157	42	76.8	53.4–110.8
28	5.97	37	3.87	24	9	115	47	95.0	55.4–166.1
29	4.11	34	2.18	18	12	65	30	116.0	64.0–218.1
30	6.99	53	6.73	51	11	201	57	64.4	42.9–96.7
31	11.5	95	10.4	86	12	310	69	68.4	50.3–93.0
32	7.35	76	5.32	55	15	159	44	85.4	59.4–123.4
33	4.06	28	1.74	12	10	52	30	142.5	70.9–306.9
34	8.42	58	4.93	34	10	147	51	105.1	67.7–165.8
35	6.41	53	3.75	31	12	112	40	105.3	66.4–169.9
36	5.17	57	3.99	44	16	119	36	80.1	53.0–121.7
37	8.39	52	4.84	30	9	144	53	106.7	66.9–173.5
38	5.20	43	9.31	77	12	278	65	34.7	23.2–51.2
39	11.7	97	7.86	65	12	235	60	92.1	66.4–128.6
40	4.23	35	6.05	50	12	180	52	43.5	27.3–68.4
41	10.2	84	7.26	60	12	216	57	86.5	61.2–123.0
42	8.89	98	6.44	71	16	192	47	85.3	62.0–117.9
43	4.66	61	4.05	53	19	121	34	71.2	48.3–105.2
44	7.18	89	6.21	77	18	185	43	71.5	51.9–98.7
45	6.82	47	1.60	11	10	48	28	257.7	134.1–546.2

Note: Density of tracks in the external detector (low-uranium mica) ρd = 4.08 ± 2.98 path/cm^{-2} × 10^5.

Table 1. (Contd.)

Grain number	ρs	Ns	ρi	Ni	Area	U ± 2se		Grain age	Age* ±95%
46	7.40	51	6.82	47	10	201	60	67.9	44.6–103.3
47	4.30	74	3.25	56	25	96	26	82.5	57.4–119.3
48	4.60	38	3.39	28	12	100	38	84.6	50.6–143.3
49	11.8	73	3.06	19	9	91	41	235.6	142.1–411.9
50	6.29	52	4.84	40	12	143	46	81.1	52.6–126.0
51	6.82	94	4.43	61	20	131	34	96.1	68.7–135.3
52	10.5	87	3.39	28	12	100	38	191.7	124.5–304.6
53	5.01	69	2.54	35	20	75	26	122.5	80.5–189.9
54	6.53	54	2.66	22	12	79	33	151.8	91.4–261.6
55	4.19	26	3.39	21	9	100	44	77.3	41.8–144.3
56	6.35	70	7.89	87	16	233	52	50.4	36.1–70.1
57	7.98	66	5.81	48	12	171	50	85.8	58.2–127.5
58	5.13	53	8.03	83	15	237	54	40.1	27.7–57.4
59	3.82	79	4.11	85	30	121	27	58.2	42.1–80.3
60	7.74	80	4.45	46	15	131	39	108.3	74.3–159.5
61	6.53	54	5.81	48	12	171	50	70.3	46.7–106.2
62	6.41	53	6.89	57	12	204	55	58.2	39.1–86.4
63	4.16	43	4.35	45	15	129	39	59.8	38.3–93.1
64	5.94	86	2.63	38	21	78	25	140.4	94.9–211.8
65	3.41	61	2.62	47	26	77	23	81.0	54.4–121.5
66	4.87	47	5.08	49	14	150	44	60.0	39.2–91.6
67	6.53	54	3.99	33	12	118	41	101.9	64.9–162.4
68	4.23	35	5.81	48	12	171	50	45.7	28.6–72.3
69	5.32	55	2.52	26	15	74	29	131.2	81.1–218.0
70	5.52	76	5.66	78	20	167	39	61.0	43.7–85.0
71	1.52	84	1.74	96	80	51	11	54.8	40.2–74.5
72	6.00	62	7.16	74	15	212	51	52.5	36.7–74.8
73	5.22	36	5.81	40	10	171	55	56.4	34.8–90.8
74	6.89	57	8.35	69	12	247	61	51.8	35.6–74.8
75	5.13	53	6.19	64	15	183	47	51.9	35.2–76.1
76	5.00	31	4.84	30	9	143	52	64.6	37.8–110.6
77	5.81	48	1.69	14	12	50	26	210.3	115.4–411.1
78	4.60	38	6.05	50	12	179	51	47.7	30.3–74.2
79	7.84	81	5.71	59	15	169	45	85.7	60.3–122.3
80	4.96	41	4.35	36	12	129	43	71.2	44.3–114.8
81	5.64	70	6.21	77	18	183	43	56.9	40.4–80.0
82	3.54	39	4.63	51	16	137	39	48.0	30.7–74.3
83	4.43	61	2.54	35	20	75	26	108.4	70.5–169.6
84	5.81	48	6.05	50	12	179	51	60.1	39.5–91.3
85	3.87	32	4.11	34	12	121	42	58.9	35.1–98.5
86	7.18	99	3.77	52	20	111	31	118.4	83.7–169.5
87	4.17	23	2.54	14	8	75	40	102.0	50.6–214.1
88	6.24	43	2.18	15	10	64	33	176.5	97.1–341.1
89	6.53	54	2.54	21	12	75	33	158.9	95.0–276.7
90	3.43	71	1.11	23	30	33	14	190.3	118.2–318.7

Note: Density of tracks in the external detector (low-uranium mica) ρd = 4.12 ± 2.97 path/cm^{-2} × 10^5; U content in glass-dosimeter (CN-5) 12.17 ppm; factor Z = 305.1 ± 6.91; the area unit is 6.89 cm^{-2} × 10^{-7}; ρs is density of ^{238}U spontaneous decay tracks, Ns/cm^{-2} × 10^{-6}; Ns is calculated number of spontaneous decay tracks; ρi is density of induced fission tracks Ni/cm^{-2} × 10^6; Ni is calculated number of induced fission tracks; U is uranium content, ppm; ±se is standard error of the U content determination; age*—interval of age determination ±95%.

Table 2. Fission-track ages of detrital zircons from sandstones of the Lesnaya Group (northern Kamchatka)

Sample number	Number of grains dated	Age of populations (BinomFit v.1.8—Brandon, 1996)		
		P1	P2	P3
L1	45	46.0 ± 2.7		107.3 ± 7.0
		Nf = 22.1		Nf = 22.9
		W = 22%		W = 25%
L2	90	48.1 ± 5.0	78.1 ± 5.8	116.0 ± 8.6
		Nf = 6.1	Nf = 47.4	Nf = 36.6
		W = 19%	W = 22%	W = 23%
L4	90	58.1 ± 4.2	83.3 ± 6.3	130.5 ± 14.9
		Nf = 32.6	Nf = 46.1	Nf = 11.4
		W = 23%	W = 24%	W = 24%
L9	90	47.0 ± 3.8	70.8 ± 5.7	104.0 ± 11.9
		Nf = 16.9	Nf = 50.4	Nf = 22.7
		W = 19%	W = 21%	W = 25%
L10	90	53.9 ± 3.4	87.5 ± 6.2	176.5 ± 23.8
		Nf = 35.7	Nf = 45.3	Nf = 9.0
		W = 21%	W = 22%	W = 29%
L11	90	50.4 ± 5.6	70.6 ± 6.6	109.7 ± 25.0
		Nf = 17.9	Nf = 58.7	Nf = 13.4
		W = 22%	W = 24%	W = 26%
L12	67	43.7 ± 3.4	70.6 ± 4.4	107.0 ± 12.2
		Nf = 11.3	Nf = 44.6	Nf = 11.1
		W = 19%	W = 22%	W = 23%
L13	89	55.5 ± 3.5	93.0 ± 4.8	
		Nf = 30.4	Nf = 58.6	
		W = 21%	W = 23%	
L17	90	54.5 ± 10.4	84.6 ± 6.5	134.6 ± 18.9
		Nf = 4.0	Nf = 58.9	Nf = 27.0
		W = 20%	W = 20%	W = 24%

Note: (Nf) number of grains statistically attributed to a given population; (W) relative standard deviation of a peak (characteristics peak "width" expressed in percent, after Brandon, 1996). The age determination error ±1σ corresponds to the standard deviation of the mean peak position for Nf grains. Zircons are dated using the external detector method (Hurford and Carter, 1991). Zircon grains were pressed into FEP Teflon *MT* plates 2 × 2 cm^2 in size. Two plates were prepared for each sample. The abraded plates were polished with diamond paste (9 and 1 μm) and Al_2O_3 paste (0.3 μm) at the final stage. The plates were etched by NaOH-KOH compound at the temperature of 228°C during 15 (first plate) and 30 hours (second plate). After etching, the plates covered with detector (mica with a low U content) were exposed to irradiated under the thermal neutron flux of 2×10^{15} neutron/cm^2 (reactor of the Oregon University). The zircon age standards Fish Canyon Tuff (FCT) and Buluk Tuff (BL), and also the glass-dosimeter (CN-5) with known U content (Hurford, 1998) were irradiated simultaneously with samples. Microscope Olympus BH-P with an automated system and digital plotting board (maximum magnification ×1256, dry method) was used to calculate density of tracks. Z-factor calculated on the basis of 10 age standards (6 FCT and 4 BL) is 305.01 × 6.91 (Hurford, 1998).

important to note that old zircon grains (> 500 Ma) and grains with a high U content (> 500 ppm) usually show the very high density of fission tracks, and their dating appears to be impossible. Moreover, the metamict, usually Precambrian zircons dissolve under long chemical etching applied in our procedure of sample treatment (see explanations for Table 2). Thus, we were unable to get information about the Early Paleozoic and Precambrian zircons from the Lesnaya Group, though they definitely occur in rocks.

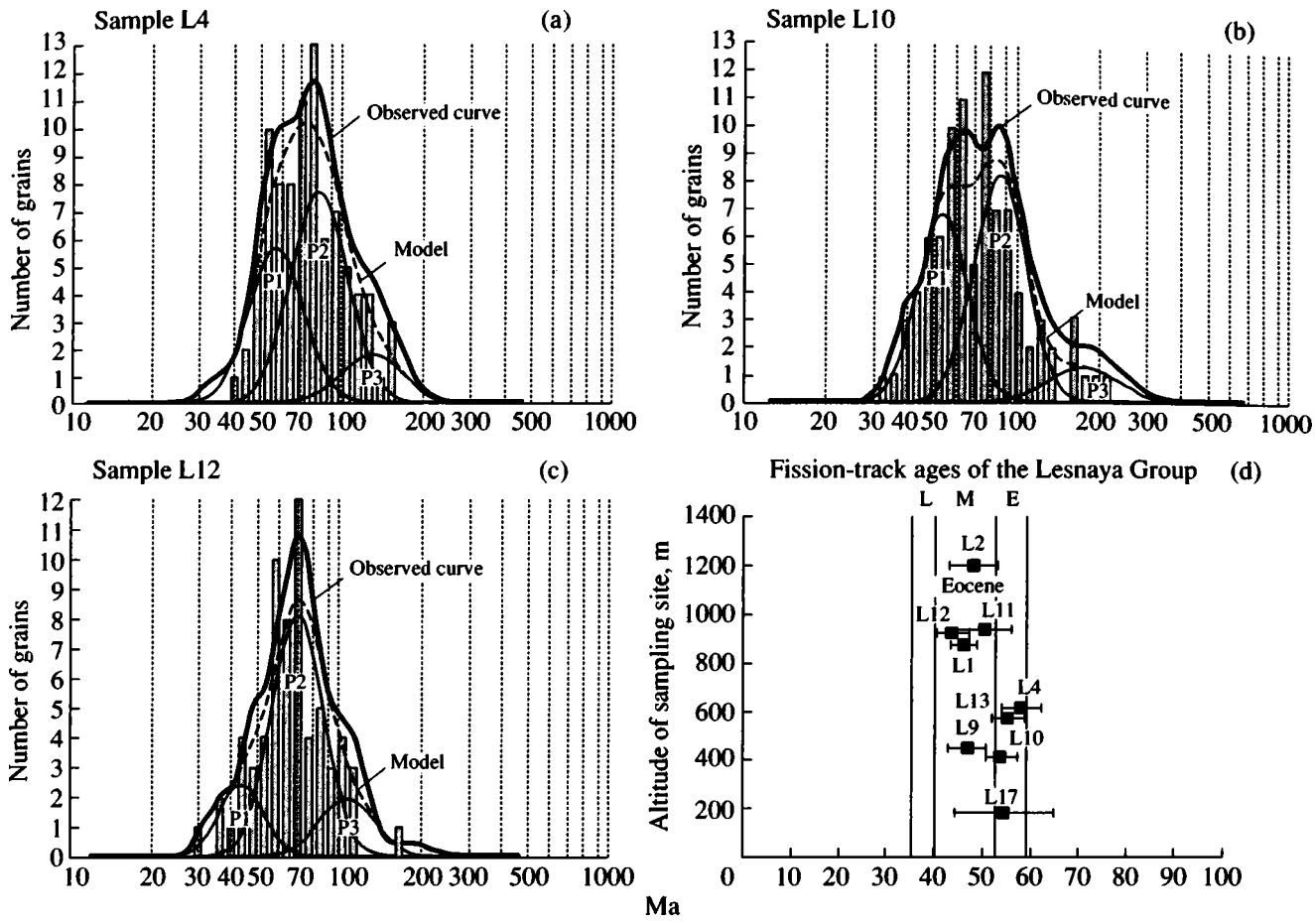

Fig. 2. Histograms (a, b, c,) of fission-track ages of detrital zircon from sandstone samples of the Lesnaya Group: the observed (solid line) and model (dashed line) curves, the later estimated using the BinomFit 1.8 program by Brandon (1996); P1, P2, and P3 are peaks of different-age populations (see Table 1) fitting the model curves; (d) ages of young zircon populations distinguished in the studied samples (age determination error is $\pm 1\sigma$) versus altitude of sampling sites. The fission-track ages of young zircon populations are interpreted as indicators of accumulation time of the Lesnaya Group (see text for explanations). Eocene substages: (E) early, (M) middle, and (L) late. Indices L1, L2, etc., correspond to sample numbers in Table 2.

COMPOSITION OF SANDSTONE FROM THE LESNAYA GROUP

The Lesnaya sandstones were previously studied by Shapiro *et al.* (1993). Since the knowledge of the rock composition is important for understanding the nature of provenances, we studied the composition of the samples, zircons from which were used for age determinations (Table 3).

All the studied sandstone samples are compositionally similar (Table 3) and, according to the classification by Pettijohn *et al.* (1976), they are typical graywackes having 23–35% of fine-grained matrix. Among grains, there are rock fragments (36–47%), quartz (27–33%), and feldspar (21–31%). According to the average composition, the samples (Q30F26L44, Fig. 3a) corresponds to lithic graywackes (Pettijohn *et al.*, 1976) or feldspar–quartz graywackes (Shutov *et al.*, 1972). Their feldspar fraction predominantly consists of plagioclase monocrystals, whereas feldspar aggregates make up only 15–35% in total. Alkali plagioclase (albite) represents up to 5–30% of all feldspars. Individual aggregates of plagioclase and quartz are also present. Monocrystalline quartz shows clear undulating extinction and abundant dusty inclusions. Its clear unstrained grains are rare. Polycrystalline grains make up 15–30% of the total quartz fraction. Ore and colored minerals are very rare. The latter are often represented by small flakes of white and brown mica and, occasionally, by amphibole. Large rounded zircon grains are most common among the colored minerals.

Clasts of volcanic rocks, devitrified glass included, slightly dominate over sedimentary lithic fragments (Fig. 3b). Volcanic clasts with felsitic and microlitic textures prevail over those with granular texture. Only feldspar was found in volcanic rocks as small phenocrysts. Sedimentary rocks are represented mainly by mudstone, siltstone, and siliceous–clayey rocks probably representing original tuffs (Table 3). Chert, sandstone, coaly mudstone, shale, siltstone, and plant debris

Table 3. Composition of sandstone samples from the Lesnaya Group

Sample	Qm	Qp	Qq	P	F	K	Lvl	Lvm	Lvf	Lvv	Lm	Lssh	Lsa	Lss	Lsch	Lst	Ls	Op	nOp	U	T	Mtx	Aut	Age*
L12	62	21	9	55	16	1	9	18	27	19	2	4	23	7	4	7	9	–	1	6	300	89	9	43.7 ± 3.4
L1	63	12	4	68	22	1	8	22	25	22	6	5	20	5	2	6	–	3	1	5	300	116	17	46.0 ± 2.7
L9	62	12	3	62	24	1	3	9	29	16	2	2	35	15	9	4	1	–	–	11	300	119	27	47.0 ± 3.8
L2	75	16	14	52	7	–	2	14	27	8	7	8	34	4	10	5	2	2	2	11	300	83	8	48.1 ± 5.0
L11	64	17	3	72	6	1	6	18	30	15	3	4	30	8	7	7	1	1	–	7	300	89	22	50.4 ± 5.6
L10	66	19	3	65	18	–	4	23	24	13	2	1	32	6	7	9	–	2	–	6	300	102	14	53.9 ± 3.4
L17	83	11	3	75	14	–	4	14	18	44	2	1	9	3	3	5	3	1	2	5	300	97	3	54.5 ± 10.4
L13	66	17	4	58	10	–	10	28	14	39	6	–	16	1	9	10	3	–	–	9	300	96	7	55.5 ± 3.5
L4	75	15	3	63	4	–	12	16	25	33	5	4	18	4	4	9	–	–	–	10	300	132	36	58.1 ± 4.2

Note: Main detrital components: Qm, monocrystalline quartz; Qp, polycrystalline quartz; Qq, quartzite; P, Ca-plagioclase (colored); F, Na-albite (uncolored); K, potassium feldspar; Lvl, volcanics with lath-shaped crystals; Lvm, microlitic volcanics; Lvf, felsitic volcanics; Lvv, devitrified glass; Lm, metamorphic rocks; Lssh, shale; Lsa, mudstone, aleuropelite; Lss, mudstone, sandstone; Lsch, chert; Lst, fine-grained tuffaceous–sedimentary rock; Lso, other sedimentary rocks, bioclasts included; Op, ore mineral; nOp, colored mineral (mica, amphibole, pyroxene, etc.); U, unidentifiable grains; T, total number of counted points; Mtx, matrix (cement included); Aut, secondary minerals.

* Age of the youngest zircon population interpreted as indicator of accumulation time of the Lesnaya Group.

are found as individual grains. Persistent but insignificant admixture of metamorphic rocks is represented by phyllite, greenschist, mica schist, and micaceous quartzite clasts (Table 3b).

DISCUSSION

Fission-track ages of individual zircon grains from deposits of the Lesnaya Group vary widely from 44 to 176 Ma. The fact suggests that deposits of the group have not been heated after deposition above the critical temperature of the track system closure in zircons (215–240°C). Hence, the upper horizons of the Lesnaya Group, where zircons yielded the age value of 43.7 ± 3.4 Ma, cannot be older than the middle Eocene. This considerably changes the formerly accepted age of the Lesnaya Group, the accumulation period of which should be extended to the lower half of the middle Eocene. We emphasize that this inference does not contradict any direct age interpretation of the Lesnaya Group. Moreover, the dates obtained enable correlation of the Lesnaya Group with the Ukelayat flysch sequence, the upper part of which is quite reliably attributed to the Eocene on the basis of fission-track dating (Garver *et al.*, 1998; Solov'ev *et al.*, 1998).

Some consequences of new dating results require a brief discussion. The time interval, during which zircons the youngest zircon population was transported from provenances to the sedimentation basin, could be as long as several million years (Brandon and Vance, 1992; Garver *et al.*, 1999). In our case, however, the difference between the age of young zircons (about 45 Ma) and sedimentation time cannot be as great, since deposits of the Lesnaya Group are unconformably overlapped by volcanics of the Kinkil' Formation, the lower horizons of which are characterized by the oldest K/Ar date of 46.5 ± 0.8 Ma (Gladenkov *et al.*, 1991). Hence, the fission-track age of young zircons coincides within the limits of analytical error (3–4 Ma in our runs) with the time of sedimentation. There are known some other regions, where the young zircon population was associated with volcanism synchronous to sedimentation in the flysch trough (Brandon and Vance, 1992; Garver and Brandon, 1994). In our case, this assumption finds confirmation in morphology of zircon grains. The studied zircons of the youngest population are mainly colorless, idiomorphic crystals of typical volcanogenic origin, which did not experience an appreciable transportation and arrived in the basin soon after their cooling. The morphology of older zircons is more diverse: grains of moderate roundness grade are dominant, whereas grains and idiomorphic crystals are rare. The age range of the youngest zircon population from different samples (43.7 ± 3.4–58.1 ± 4.2 Ma) indicates the stratigraphic range of the interval sampled and, probably, the duration of the synchronous volcanism. The Paleocene volcanics known in the western coast of Kamchatka (Gladenkov *et al.*, 1997) can be considered as source rocks of young zircons accumulated in the Lesnaya Group. In the current structure of the peninsula, volcanics of that age are exposed in the Utkholokskii and Khairyuzov capes, as well as near the Shamanka River mouth.

Thin beds of fine tuffs are present among deposits of the Lesnaya Group. Sandstone beds with a considerable amount of pyroxene and amphibole among dominant clasts of volcanic rocks were also detected in some sections of the Lesnaya Group (Grechin, 1979). Lenticular members of tuffaceous sandstones and tuffs are described among the Ukelayat trough deposits correlative with the Lesnaya Group (Ermakov and Suprunenko, 1975), and volcaniclastic varieties are dis-

tinguished among sandstone beds of variable composition (Ermakov and Suprunenko, 1975; Kazimirov *et al.*, 1987). We should emphasize, however, that the fresh tuffaceous material has not been recognized in thin sections of the studied sandstone samples. Clasts resembling in morphology ash particles, or rock fragments with pumiceous structure have not been distinguished as well. Quartz grains having habit typical of phenocrysts in acid volcanics are absent. Zonal plagioclase crystals are also unknown in these rocks. Pyroxene, amphibole, and titanomagnetite represent a minor part of the heavy fraction (Shapiro *et al.*, 1993). It should be noted as well that we sampled thick beds of medium- to coarse-grained sandstones angular mudstone fragments. All these features are characteristic of the fluvial turbidite facies of submarine fans, which show minimal grading and sorting of detrital material. Most grains are angular, and soft rocks like mudstones are frequent among them. These characteristic features of the studied sandstones exclude a possibility to explain the absence of fresh tephra by its reworking and disintegration during a long transportation.

Thus, we suspect that the volcanic source is not the only possible explanation for origin of the young zircon population, the fission-track age of which was concurrent to sedimentation time of the upper parts of the Lesnaya Group. It is likely as well that voluminous hypabyssal acid to intermediate intrusions, which originated in the provenance at the end of the Paleocene and in the first half of the Eocene, but had no relation to the synchronous volcanism, could be taken for the additional source of zircons. If the intrusive activity was synchronous to the rising of landmasses subjected to denudation, then most of igneous rocks could be brought to the erosion surface in the middle Eocene. Abundant feldspar and subordinate quartz–feldspar (including micropegmatite) intergrowths occurring among clasts of the sandstones sampled could be derived from such intrusive rocks. If the intrusive bodies were formed at a depth of 2–3 km, then the time interval between the zircon formation and its appearance in sediments would be not greater than the determination error of fission-track ages, provided that the bodies rose up to the surface at 500–1000 m/m.y. If the hypabyssal intrusions happened to be the main source of young zircons, we meet certain difficulties by interpreting variations in the average age of young zircon populations in different samples. If we assume that they indicate ages of sampled sediments, this would mean the constant rate of rising of intrusive bodies to the surface during the whole period of accumulation of the Lesnaya Group. In such a case, the provenance should be eroded down to the depth of 5 km during 10 m.y. so that the older intrusions would be eroded completely, while younger intrusive bodies were brought to the surface. Admitting such a deep erosion, we may expect considerable changes in composition of sandstone with time. However, we do not see changes of that sort in sampled sandstones. Hence, it more probable that we

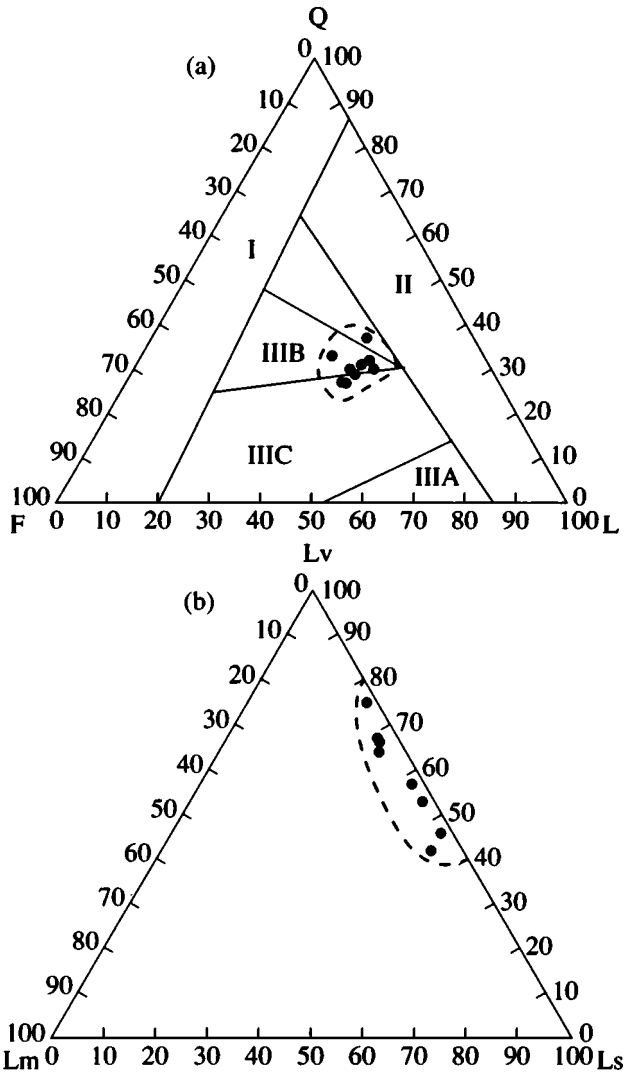

Fig. 3. FLQ diagram (a) for sandstones of the Lesnaya Group: Q, quartz (without silicate rock and quartzite), F, feldspar, L, rock fragments. Fields in the diagram correspond to following type provenances (Dickinson *et al.*, 1979): (I) continental massifs; (II) orogens; (III) magmatic arcs eroded poorly (A), deeply (B), or moderately (C). Dashed contours outlines the compositional field of the Lesnaya Group sandstones.

Lm-Lv-Ls diagram (b) characterizing proportions of lithic clasts in sandstones of the Lesnaya Group: (Lm) metamorphic, (Lv) volcanogenic, and (Ls) sedimentary rocks; dashed line limits the compositional field of the Lesnaya Group sandstones.

sampled a narrow stratigraphic interval of the youngest beds of the Lesnaya Group, and the age variations of young zircon populations reflect changes in the drainage areas that supplied the basin of sedimentation with detrital material. In this case, the land rise could be slower and the erosion not so deep.

Zircons, the fission-track age of which is synchronous or almost synchronous to sedimentation, may appear in the provenance as the result of a rapid exhu-

mation of young intrusions and any zircon-bearing rocks from the depth, where the temperature exceeded the blocking one. If the exhumation rate exceeded 2000 m/m.y. and the geothermal gradient in the provenance was 50°C, then the time difference between the zircon cooling in the initial collector and its burial in sediment was not greater than 3 m.y. As the Lower Paleogene sequences of the western Kamchatka coast are represented by coarse molasses (Gladenkov *et al.*, 1997), a fast rise and deep erosion of individual blocks in the provenance are quite possible. The high geothermal gradient assumed above is plausible, because manifestations of the Paleocene–Eocene volcanism are known in the western Kamchatka. In this case, we should assume a considerable differentiation of tectonic movements that would mean that the most frequent zircons (population P2) are derived from rocks cooled in the Late Cretaceous, some others (population P3) are related in origin to the basement salients, which experienced the pre-Late Cretaceous thermal impact, and the young population (P1) characterizes blocks which rapidly rose from the depth, where the temperature exceeded the blocking one. In this case, the variable average ages of young zircon populations from different samples can be explained by different exhumation rates of individual blocks.

The newly established upper limit of the Lesnaya Group is important for understanding its relationships with the Paleocene–lower Eocene molasses of the western Kamchatka coast (Gladenkov *et al.*, 1997). According to our data, the upper part of the Lesnaya Group and molasses of the western Kamchatka could be considered as facies analogues of the Paleocene–early Eocene time. In such a case, it is understandable why the latter do not occur above the Lesnaya Group. At the same time, facies transitional between the molasses and Lesnaya Group have never been described, though Grechin (1979) mentioned individual thin coal measures occurring among deposits of the Lesnaya Group and suggesting possible facies interrelations between molasse and flysch. Searching for facies of this kind is an important problem to be solved. Moreover, new data imply important tectonic consequences: folding of the Lesnaya Group and formation of the Lesnaya thrust fault, an important tectonic suture, happened during a short period of time about 45 Ma ago, when sediments in the upper part of the Lesnaya Group were still unconsolidated. Data on the folded structure of the Lesnaya Group suggest that deformations affected the pliant sediments (Shapiro and Solov'ev, 1999).

We hope the information presented may give impetus to a new study and reinterpretation of many problems of regional geology.

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Resolution of the Third All-Russian Meeting "General Problems of Precambrian Stratigraphy"

The Third All-Russian meeting "General Problems of Precambrian Stratigraphy" was organized by Permanent Commissions on the Lower and Upper Precambrian of the Interdepartmental Stratigraphic Committee, Scientific Council on Precambrian Geology, and Regional Interdepartmental Stratigraphic Commission (RISC) for Northwestern Russia. The meeting was held in Apatity on June 13–15, 2000. The meeting was necessary to improve and detail the Lower Precambrian general stratigraphic scale accepted in Russia, as it serves as the basis for all investigations of the relevant part of the geological record.

Investigations performed during the last decade after approval of the recently valid Precambrian stratigraphic scale of Russia (Ufa, 1990) brought new factual data on the Lower Precambrian isotopic geochronology, regional geology, and stratigraphy of Russia and CIS countries. As a result, new Lower Precambrian stratigraphic scales were proposed at or approved by the Interdepartmental regional stratigraphic meetings (IRSM) for key regions of Russia: Karelia, Kola Peninsula, Voronezh Massif, and Aldan Shield. A succession of supracrustal sequences recovered in Karelia is traditionally considered as a basis for elaborating the general Lower Precambrian stratigraphic scale of Russia. The stratigraphic completeness and quite adequate modern knowledge of this succession allow the upper (Karelian) part of the succession to be considered as representing hypostratotype of the Lower Proterozoic.

The main achievements in the study of the Lower Precambrian stratigraphy became possible when Russian geologists acknowledged the principal significance of the chronostratigraphic approach to subdivision of the Precambrian and begun to apply recommendations of the Stratigraphic Code (1992) to the relevant studies. Exactly this approach enabled the historical–geological substantiation of boundaries between main Precambrian units, the correct application of isotopic dates for age calibration of their boundaries, and the detailing of the Precambrian stratigraphic scale of Russia. The accumulated data on composition of microfossils and stromatolites in the Upper Archean and Lower Proterozoic successions of North Eurasia are undoubtedly of a great interest, but they cannot be used so far for the general stratigraphic purposes.

In total, 97 specialists from 20 scientific and industrial organizations of Moscow, St. Petersburg, Petrozavodsk, Apatity, Murmansk, Zapolyarnyi, Monchegorsk, Khabarovsk, Magadan, and Vladivostok attended the meeting. In addition, geologists from Norway and Belarus took part in the discussion. Extended abstracts of 101 reports presented by scientists from 31 Russian and 7 foreign organizations were published.[1] The preparatory work before the meeting included the regional interdepartmental stratigraphic meeting on the Lower Precambrian geology of North Eurasia held in Petrozavodsk in June 1999. The stratigraphic scheme approved at this regional meeting, as well as an alternative version of the Lower Precambrian chronostratigraphic scale of North Eùrasia presented there by specialists from VSEGEI, are of basic significance for the specified general stratigraphic scale of Lower Precambrian in Russia approved in Apatity.

The participants got acquainted with 28 oral reports and 39 poster presentations dedicated to the Archean and Lower Proterozoic geology and 35 specialists participated in the discussions. The reports dealt with the new data on isotopic geochronology, regional geology, stratigraphy, metamorphism, and magmatism in main distribution areas of the Lower Precambrian sequences of East Europe (including Ukraine, Belarus, Finland) and North Asia. Several reports considered conceptual aspects of the Precambrian stratigraphy and spatial–temporal evolution of settings, where Precambrian supracrustal rock assemblages were formed and experienced transformations; some reports were devoted to cosmocentric and synergetic aspects of geology and to cyclicity of geological processes.

When these materials have been discussed, the meeting noted that the new data obtained during the last decade can improve the general stratigraphic scale of the Archean and Lower Proterozoic of Russia approved in 1999, and that this improvement can increase the efficiency of investigations on the Lower Precambrian geology, geodynamics, and mineral resources. The data can be used as well for detailing of legends for the new generation of geological maps scaled 1 : 1 000 000 and 1 : 200 000. Different views on the stratigraphic scale, which have been expressed at the meeting, reflect, to a significant extent, a shortage of data on the event interpretation, hierarchy, and isotopic age of boundaries between main stratigraphic units. The additional negative factor is the absence of officially approved GSSP

[1] Materials of III All-Russian Meeting "Main Problems of the Precambrian Stratigraphy", Apatity: Geol. Inst., Kola Nauchn. Tsentr, Ross. Akad. Nauk, 2000.

(limitotypes) for the stratigraphic units, which could be accepted for stratotypes of general units.

The discussion of presented materials led the meeting to the following conclusions:

1. The chronostratigraphic principle of subdividing the Precambrian that is traditional for Russian geologists is undoubtedly advantageous as compared to the popular chronometric principle. Its advantages are as follows: (a) this is the common principle of constructing the stratigraphic scale for the entire observable stratisphere; (b) it presumes the substantial expression of all the defined general units and the possibility to obtain complex characteristics (event, isotopic-geochronological, paleontological, chemostratigraphic, paleoclimatic, and others) of units and their boundaries; and (c) it opens a possibility to apply several interchangeable features for correlation of stratigraphic units.

2. In line with the chronostratigraphic principle of scale construction, as is accepted at the meeting, the specified general Lower Precambrian stratigraphic scale of Russia leans upon the analysis of succession, relationships, and compositional properties of the type rock complexes characterizing general units and upon the substantiation and fixation of their boundaries in the selected stratotype sections. In the type regions, these boundaries are determined by different geological events, the rank of which is comparable in scale with the boundary rank.

3. The specified general Lower Precambrian stratigraphic scale of Russia (Table) inherits the accepted main units of the scale approved at the Ufa meeting in 1990 and principles of constructing and defining the system of hierarchical general units (acrothem, eonothem, erathem). Simultaneously, the new scale is advantageous as compared with the former scale. In particular, the isotopic ages of the Upper Archean lower boundary is determined more accurately; the Upper Archean (Lopian) Eonothem includes three erathems; the boundary between two erathems of the Lower Proterozoic (Karelian) changed its position, age, and event interpretation; and positions of most boundaries between general units are fixed in the sections of stratotype regions.

4. The isochron and particularly concordant U–Pb zircon age determinations for volcanics represent the isotopic–geochronological information most important for stratigraphy, whereas the isochron Sm–Nd, Pb–Pb, and Rb–Sr dates for bedded, intrusive, and highly metamorphosed rock assemblages play a subsidiary role in solving stratigraphic problems of the Lower Precambrian. The complicated evolution of Lower Precambrian rocks requires a thorough mineralogical and structural-geochemical (in case of metamorphic rocks) investigation of objects in order to adequately interpret the geological significance of obtained dates.

Some researchers of the Aldan shield, Voronezh massif, and northeastern Russia argued that the limited number of isotopic dates older than 3200 Ma, which are obtained for granulite–gneiss complexes, cannot discard the traditional opinion that these rocks are presumably the oldest ones. As these researchers believe, all isotopic systems of granulite–gneiss complexes were multiply disturbed under PT conditions of their formation, and the dates obtained for them usually characterize the terminal moments of endogenic perturbation (closure of isotopic systems).

5. When correlating the Lower Proterozoic (Karelian) deposits, geologists should lean upon a complex of interchangeable features and take into consideration the facies variability and diachronous character of boundaries between formations and groups composing the particular general units. Isotopic–geochronological dates corresponding to the manifestation time of endogenic processes are most important for correlation of the Archean (particularly of the Lower Archean) general units. The establishment of both their hierarchy and complex of correlation criteria still represent one of the main tasks in the study of the Archean Acrothem.

6. The Archean–Proterozoic boundary in the general stratigraphic scale of Lower Precambrian in Russia is perceived as a level of most important event. It marks the main restructuring stage in the eastern Baltic Shield and separates the eroded granite–greenstone assemblages terminating formation of the Late Archean craton from overlying sedimentary–volcanogenic rocks of the Proterozoic Sumian Superhorizon that recorded formation of a new structural plan in the region possessing the reworked products of highly mature weathering crusts. The isotopic age of this boundary is estimated to be 2550 Ma based on the U–Pb dates obtained for the following rocks: (a) geologically youngest igneous rocks of the granite–greenstone areas in Karelia (2556–2554 Ma); (b) acid volcanics from the Sumian Ozhijarvi Formation (2449–2442 Ma); (c) oldest gabbro–norite intrusions (2505–2498 Ma) and granites of the Korman massif (2449 Ma), the formation of which is related to the rifting at the Sumian–Sariolian time. It was proposed to place this boundary either at the base of the Ozhijarvi Formation in the Shuozero structure, or at the base of the Okunevo Formation in the northeastern limb of the Lekhta synclinorium.

7. The Archean was subdivided into two major general units, which are viewed as eonothems—Lower Archean (Saamian) and Upper Archean (Lopian). The boundary between these units separates the oldest tonalite–trondhjemite–granodiorite gneiss complex (TTG association) known in the Baltic and Ukrainian shields and Voronezh Massif, where it includes fragments of oldest supracrustal rocks, from younger successions of well-preserved typical greenstone belts best represented in the Voronezh Massif and Ukrainian Shield. Supracrustal Lower Archean rocks are those of the Kosivtsevo and Zelenaya Rechka complexes (3265–3100 Ma) in the Ukrainian shield, and of the Volotsk complex (3.4 Ga) in the Baltic Shield. The old-

est bedded rocks of the Upper Archean are represented by metavolcanics of the Aleksandrovka Formation (3265–3100 Ma) widespread in the Voronezh Massif and by the sedimentary–volcanogenic Konka Group (3155–3110 Ma) of the Ukrainian Shield, clastic zircons of which are 3200 Ma old. Position of the Lower–Upper Archean boundary in particular sections is not established precisely so far, but its isotopic age is estimated to be 3200 Ma. This age value is based on U–Pb dates obtained for supracrustal rocks separated by this boundary (see above) and oldest TTG associations of the Baltic Shield (3500–3210 Ma), Ukrainian Shield (3760–3250 Ma), and Voronezh Massif (up to 3360 Ma). Some researchers of the Aldan Shield argue that the Saamian cannot represent a unit of the general scale, since neither a stratotype region, or stratigraphic section is selected for it, and that the gneiss–granulite complexes of the Aldan–Stanovoi region (Aldanian, Kurultinian) only can be used as a model for subdividing the Archean. In their opinion, the latter represent the Archean in its classical understanding, lack intraformational unconformities and preserve primary features necessary for the stratigraphic scale elaboration.

8. The Upper Archean (Lopian) includes three units of the erathem rank corresponding to sedimentary–volcanogenic deposits of three generations of greenstone belts. The general succession of these generations is inferable from the analysis of the composite geological record of the Baltic and Ukrainian shields and Voronezh Massif.

The Lower Lopian (3200–3000 Ma) includes the Konka Group of the Ukrainian Shield and Aleksandrovka Formation of the Mikhailovka Group of the Voronezh Massif (the corresponding isotopic dates are cited above). Sedimentary–volcanogenic rocks of the same age have not been established in the Baltic and Aldan shields.

The Middle Lopian (3000–2800 Ma) signifies the incipient formation of the next generation in greenstone belts best represented in the Baltic Shield. The type section of this erathem is composed of metasediments and metavolcanics of the Khautavaara Group of Karelia. The lower boundary of the Middle Lopian can be fixed at the base of the mentioned group in the Khautavaara structure. Its age is estimated to be 3000 Ma according to isotopic dates obtained for the Vistukkalampa Formation of the Khautavaara Group (2995–2945 Ma), on the one hand, and in accord with the minimal U–Pb age (3113 Ma) of the TTG association underlying the latter, on the other. The Middle Lopian includes the Kolmozero Group in the Kola Peninsula, the lower part of the Lebedinskii Formation of the Mikhailovka Group in the Voronezh Massif, and the Olondo Group in the Aldan Shield. In the Ukrainian Shield, the Middle Lopian is represented by metasediments and metavolcanics of the Belozerka Group (2960 Ma) separated by an unconformity and conglomerates from older rocks.

The Upper Lopian (2800–2550 Ma) succession is most complete in the Baltic Shield. The section of the iron-productive Gimoly Formation represents the stratotype of this unit. The formation overlies, unconformably and with basal conglomerates, greenstone rocks of the Kontok Group, the U–Pb and Sm–Nd isochron ages of which are slightly older than 2800 Ma. The lower boundary of the Upper Lopian is fixed at the base of the Gimoly Group in the Kostomuksha structure. The isotopic age of the boundary is estimated to be 2800 Ma according to minimal isotopic dates obtained for underlying Middle Lopian rocks (2805–2801 Ma) intruded by granites (2830–2810 Ma) on the one hand, and with due regard for U–Pb dates obtained for volcanics of the Gimoly Group in the Sukkozero structure (2750 Ma), on the other. In the Kola Peninsula, the Upper Lopian is represented by the Porosozero Group and by the upper part of the Lebedinskoe Formation of the Mikhailovka Group in the Voronezh massif. Supracrustal rocks of the same age have not been established in the Ukrainian Shield, and their presence in the Aldan Shield is debatable so far.

9. Three alternative schemes for the Lower Proterozoic (Karelian) Eonothem were discussed at the meeting: two-member subdivision of the eonotheme and two different versions of the three-member subdivision. All schemes are based on materials from the Karelian stratotype region. The appearance of alternative schemes is caused by different evaluation of the event significance, stratigraphic rank, and correlation potential of boundaries between regional stratigraphic units (superhorizons) in the Karelia–Kola region. In one of the three-member versions of the Karelian Eonothem approved by the interdepartmental regional stratigraphic meeting in Petrozavodsk, June 1999, boundaries between main units of the Karelian are proposed to be drawn at the base of Jatulian (2300 Ma) and Kalevian (1950 Ma) superhorizons. In the other version, they are placed at the base of the Ludicovian (2100 Ma) and Vepsian (1800 Ma) superhorizons. In the two-member version, the base of Ludicovian or Tulomozero Horizon of the Jatulian is considered as the major boundary.

After discussing these alternative schemes with consideration of materials from other regions, the participants approved the two-member subdivision of the Lower Proterozoic (Karelian) Eonothem into the Lower and Upper Karelian erathems, the boundary between which is placed at the base of the Ludicovian. This boundary marks an important reorganization in biosphere that is manifested in disappearance of the positive $\delta^{13}C_{carb}$. Jatulian anomaly of the global rank, in transition from predominant evaporite red beds to widespread black shales, and in important geodynamic events responsible for opening of paleooceanic basins. The stratotype section and point of the boundary is fixed at the base of the Zaonezhskii Formation of the Ludicovian in the Kuzaranda–Tipinitsa section of the Zaonezhskii Peninsula, where this formation overlies conformably the Upper Jatulian Tulomozero Formation. The isotopic age of the boundary is estimated to be

General chronostratigraphic scale of the Lower Precambrian in Russia

General stratigraphic scale			Age of boundaries	Type unit	Characteristic local units				Neighboring regions
Ac-rotheme	Eonotheme	Erathem			Karelia region	Kola region	Voronezh Massif	Aldan Shield	Ukrainian Shield
Proterozoic PR	Upper Proterozoic R		1650						
	Lower Proterozoic (Karelian) K	Upper Karelian K_2	1800	Vepsian* Vp	Shoksha Formation Petrozavodsk Formation			Ulkan Group	Ovruch Formation Pugachevka Formation
			1920	Kalevian* Kl	Ladoga Group	Porojarvi Group Pil'gujarvi Group		Udokan Supergroup	Klesovo Group
				Ludicovian* Ld	Suisai Formation Zaonezhie Formation	Kolasjoki Group	Oskol Group: Tim Formation		
		Lower Karelian K_1	2100	Jatulian* Jt	Tulomozero Formation Medvezh'egorsk Formation Yangozero Formation	Luchlampol' Formation (carbonate part) Kuetsjarvi Group	Oskol Group: Rogovo Formation		Krivoi Rog Group
			2300	Sariolian* Sr	Seletskoe Formation Vermas Formation	Akhmalakhty Group	Kursk Group		
			2400	Sumian* Sm	Ozhijarvi Formation Tungudskoe Formation Okunevo Formation	Seida Formation Kuksha Formation Purnach Formation			
Archean AR	Upper Archean (Lopian) L	Upper Lopian L_3	2550	Gimoly Group	Gimoly Group	Porosozero Group	Mikhailovka Group / Aleksandrov-Lebedinskoe Formation		
		Middle Lopian L_2	2800	Khautovaara Group	Khautovaara Group	Kolmozero Group		Olondo Group	Belozerka Group
		Middle Lopian L_1	3000		Vodlozero Association TTG	Tonalite–trondhjemite–gneiss (TTG) association		Iengra metamorphic association	Konka Group
	Lower Archean (Saamian) S		3200		Volotsk Sequence		Oboyan' TTG association	TTG association	Kosivtsevo Sequence

* Superhorizons of the Karelia–Kola regional scale.

2100 Ma according to dates obtained for following rocks in southeastern Finland: the Viipus diabase sill intruding the Upper Jatulian quartzites (Rukatunturi Formation) (2078 Ma), the Upper Jatulian basalts of the Kiikhteliesvaara structure (2105 Ma), and volcanics of the Jatulian–Ludicovian boundary interval (2060 Ma). Taking into consideration the last date, some participants of the meeting proposed to accept it as representing the age of the lower boundary of the Upper Karelian. In the Voronezh Massif, this boundary is placed at the base of substantially volcanogenic and black shale formations in the upper part of the Oskol Group (Tim Formation, 2094–2058 Ma; Kurbaka Formation, 2095 Ma; Belgorod Formation) overlying chemogenic–terrigenous deposits of the Lower Karelian. Analogues of the Lower and Upper Karelian erathems and boundary separating them are reliably defined also in sections of the Kola Peninsula and Ukrainian Shield (Table); they seem to be detectable in the Udokan Supergroup of Siberia.

10. The upper boundary of the Karelian Eonothem corresponds to the lower boundary of the Riphean. Its age is accepted to be 1650 Ma based on U–Pb dates obtained for volcanogenic zircons from basal units in the Lower Riphean type succession in the Bashkir anticlinorium. In the Baltic Shield, this boundary is placed at the base of the Hoglandian, where the U–Pb age of volcanics is 1640–1638 Ma.

11. The participants agreed to present the updated general scale of the Lower Precambrian in Russia together with this resolution to the Interdepartmental Stratigraphic Committee for the approval in January, 2001, and to publish it for the immediate use in legends of state geological maps of the new generation.

12. The participants emphasize that crucial tasks of the further improvements of the general Precambrian stratigraphic scale are as follows: it is necessary to establish in Russia a net of reference sections and boundary standards for main stratigraphic units of the Lower Precambrian; the boundaries should be accurately dated; and relevant events need a thorough interpretation. In this connection, the meeting considers it necessary to include the relevant research themes into scientific plans of following institutions: the Division of Geological, Geophysical, Geochemical, and Mining Sciences of RAS; Ministry of Natural Resources of the Russian Federation; Institute of Precambrian Geology and Geochronology; Institute of Geochemistry and Analytical Chemistry; Geological Institute of the Kola Scientific Center, RAS; Institute of Geology, of the Karelian Scientific Center, RAS; and All-Russian Institute of Geology .

13. The meeting recommends to the Ministry of Natural Resources of the Russian Federation to use the accepted Lower Precambrian stratigraphic scale of Russia in the legends for the new generation of geological maps scaled 1 : 1 000 000 and 1 : 200 000. Taking into consideration the importance of this step, the meeting asks the Ministry to support financially the preparatory work and publishing of the Explanatory Notes to the scale. Introduction of the scale into the geological practice will stimulate a higher scientific and economical efficiency of geological mapping and prospecting.

14. The participants consider it necessary to focus attention on the following topics: deciphering of the facies–paleogeographic structure of the Karelian sedimentary basins; interpretation of stratigraphic hiatuses and their duration; study of paleoclimatic indicators of the Karelian; understanding of isotopic–geochemical and biospheric events that occurred during the Late Archean–Early Proterozoic; and analysis of relationships between sedimentogenesis, magmatism, and metamorphism. Further isotopic–geochemical researches should be preceded by the purposeful study of geological objects to be dated.

15. The participants consider as their pleasant obligation to thank for the meeting organization the Administration of the Geological Institute, the Kola Scientific Center, RAS; personally V.Z. Negrutsa, the Chairperson of the Permanent Commission on the Lower Precambrian, and T.F Negrutsa, the Science Secretary of this commission; as well as sponsors—the Russian Foundation for Basic Research, Ministry of Natural Resources of RF, and Geological Institute, the Kola Scientific Center RAS.

Apatity, June 15, 2000

Commission selected by the meeting for the resolution elaboration: A.M. Akhmedov, E.V. Bibikova, Yu.B. Bogdanov, R.F. Cherkasov, L.I. Filatova, V.A. Glebovitskii, F.P. Mitrofanov, V.Z. Negrutsa, T.F. Negrutsa, V.A. Pavlov, B.M. Petrov, B.V. Petrov, V.I. Robonen, M.A. Semikhatov (Chairperson), V.I. Shul'diner, I.L. Zhulanova.

Editorial note. The general Lower Precambrian stratigraphic scale of Russia accepted at the 3rd All-Russia Meeting on General Problems of Precambrian Stratigraphy was considered and approved by the extended bureau of the Interdepartmental Stratigraphic Committee (ISC) of Russia on February 2, 2001. The ISC bureau arrived at the conclusion to return to the traditional position of the Archean–Proterozoic boundary at 2500 Ma instead of that recommended by the meeting.

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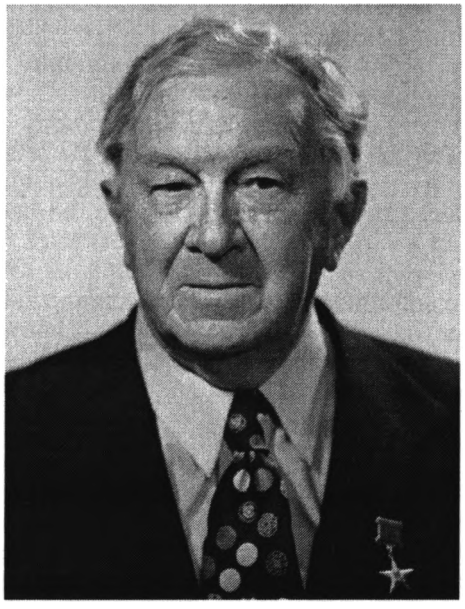
In Memory of Aleksandr Leonidovich Yanshin (1911–1999)



When science or culture happened to be left without such an outstanding person as Aleksandr Leonidovich Yanshin, we always need some time to assess properly our loss, to perceive his activity without a shadow of involuntary miscomprehension, and to realize the very main things that could be accepted as his testament. I am not sure that the time has already come, as months have elapsed too fast without a vivid presence of Aleksandr Leonidovich (he died on October 9, 1999) and his active personality is still too alive among us to realize that he has passed away and that we are indebted to his memory. Aleksandr Leonidovich is buried at Vvedenskoe Cemetery of Moscow.

What I am going to say about Aleksandr Leonidovich is only brief traits to his portrait. There is no question that a full scientific and biographical essay should be written about this eminent geologist and naturalist, an exceptional versatile man who left a bright trace in science, its history, scientific publicism and polemics, and, for sure, in the memory of several generations. A book should also be written about Academician Yanshin, as many his pupils and disciples, hundreds of specialists, scientists, cultural and industrial workers, who associated with him, are alive. Aleksandr Leonidovich was always an attentive and concerned interlocutor who impressed everybody by his inexhaustible erudition that could be unexpectedly applied to the agricultural statistics, demography, ancient history, and even geographical coordinates. His memory was phenomenal and highly exceeded the professional limits.

My personal acquaintance with Aleksandr Leonidovich happened in the second half of our lives, when we both appeared to be closely bound up first with the Siberian Division of the USSR Academy of Sciences (from 1958) and then with the Presidium of the Academy—me as Academic Secretary of the Division of Geology, Geophysics, Geochemistry, and Mining (1975–1990), and he as Vice President of the Section of Earth's Sciences (1982–1988). Later on, we became councilors of the Presidium, Russian Academy of Sciences (RAS). We have known each other even earlier, by correspondence since the late 1930s, i.e., before my trip to China in June, 1941. I remember one episode of that time very well. I came on business to Professor Afrikan Nikolaevich Krishtofovich (VSEGEI, Leningrad) to his study-room, where I met his postgraduate student Tanya Baikovskaya. She said, "Oh, Boris, Aleksandr Leonidovich Yanshin has just left us; it's a pity, you have not met him. He is a new star in Moscow geology. He is so young, elegant, courteous, and well-educated. Afrikan Nikolaevich is charmed with him so much." I am sorry to say I felt no regret. Some time later, we exchanged some critical letters. The Editorial Board of the Journal *Soviet Geology* (he has not yet been in its staff) gave him my paper on the Silurian of the Lake Balkhash region for a review, and Aleksandr Leonidovich rather boldly edited it in such a way that some conclusions appeared to be inconsistent with the content. We both were to blame for it. Afterward, the war that was just unleashed, my prolong Asian epopee, a tragic fall of Aleksandr Leonidovich into a prospect pit (1949), and different geological interests pushed aside that small disagreement. We established personal and friendly relations after a lapse of time, at the end of March, 1958, when we both were elected to the Academy of Sciences in the Siberian Division, Aleksandr Leonidovich as a Member and me as a Corresponding Member. Since that time our personal relations have not been clouded for 40 years.

I should interrupt, however, this prelude and come back to the main theme, i.e., to a feasible reproduction of some personal features and deeds of Aleksandr Leonidovich, which depict a phenomenal personality of that man. It is widely believed that Academician Yanshin did not got a complete higher education. This is formally the case, which is hardly of any importance since such persons are not at all few among splendid erudite scientists. Normal people should be shocked not by this fact, but by incompetence of many those

who got university diplomas. Such graduates seem to appear nowadays in increasing number, and the evil of specialism in science is a true trouble threatening to the moral and intellectual health of the whole nation.

Aleksandr Leonidovich was born in Smolensk on March 28/15, 1911, i.e. on the very eve of that non-calendar (as I usually say) but real 20th century, with dramatic events of which his life was tightly interwoven. It is likely that everything was quite traditional at the beginning: an intellectual family of his father, a lawyer, books, nature, the influence of spiritual interests of the society. Aleksandr Leonidovich carried from that time to all his life a special taste for the poetry of the Silver Age and for the humanities. Family relations served as good educational and fostering media, whereas the wartime and revolutionary years brought a fair amount of confusion into a systematic school studies—there were searches for some new knowledge and new ways how to get it instead of former classic schools and colleges destroyed by that time. A famous Dolton Plan has rapidly turned in this country into an abnormal brigade-laboratory method of teaching, which mutilated more than one generation of pupils. Under conditions of searching and experimenting, Aleksandr Leonidovich fished out a lucky ticket—he entered an experimental school at the Pedagogical Faculty of the Smolensk University, finished it by summer, 1928, and gained an excellent secondary education. I venture to say that 17 years in Smolensk were of critical importance for the formation of his personality of a scientist, for upbringing his gift for a nature explorer who was also endowed with the humanities and literature in general. A peculiar school, an aspiration for knowledge, and excellent memory (it has been retained for all his life) gave Aleksandr Leonidovich what a complete university education usually gives. The latter was only a formal necessity, as an independent and original intellect could easily choose ways for a further perfection and satisfaction of personal scientific interests.

No wonder that, on coming to Moscow in the autumn of 1928, Aleksandr Leonidovich omitted a common procedure of entering the university and visited selective lectures at the Geological Faculty of Moscow University. He saw his main concern in acquiring a practical geological experience. With this aim in view, he spent a year in special courses for collectors at the Research Institute of Fertilizers, and this was quite enough for a well-educated young researcher to start in summer of 1929 an independent work at the Mining–Geological Department of the institute headed by Professor A.V. Kazakov, an eminent expert in lithology of phosphorites. Phosphorites and mineral fertilizers in general became the first greatest affection of Yanshin. These entailed a wide range of interests in other problems of the scientific and applied geology, and not only in geology. That was a time of the radical reconstruction of our traditional geological survey (Geological Committee) and the time of organization of first geological institutes in the Academy of Sciences, as before 1930 the only institution of geoscience was the Peter the Great Geological Museum in Leningrad. Aleksandr Leonidovich happened to be at the very source of the impetuous rebirth of the national geology in all lines and occupied a prominent place in the science. The study of phosphorites, a keen interest in which he brought through all his life, snowballed into an extended regional research in the Caspian region, South Urals, Mugodzhary, and Kazakhstan. An excellent and inexhaustible field worker, he dived into the geology of productive basins, their lithology, stratigraphy, tectonics, and geological history. His growth as a scientist was extremely swift and struck everybody by the breadth of problems that involved him. He seems was captivated by everything as a field geologist and a naturalist. Being twenty years old (1931), he became a coauthor of the first publication, a year later he published *Tectonics of the Kargala Mountains* (1932), a significant and fundamental work that immediately put the author into the same rank with acknowledged researchers of regional geology. An excellent language of the work has engaged the attention and allowed it to hold a special place among geological papers noted for the excessive dry style.

Even among experienced and well-known geologists of Moscow, Yanshin have drawn the attention to himself by a remarkable diversity of interests and fundamental nature of research. Well known is his original insight in stratigraphy (first of all, in Mesozoic and especially Cenozoic), sedimentology, hydrogeology, the origin of mineral resources, not to mention the regional geology and tectonics of an extensive Kazakhstan area adjacent to the Urals. Academician A.D. Arkhangelsky invited him in 1936 to the Geological Institute, the USSR Academy of Sciences, where the young, 26-year old researcher got his Candidate's degree (Geol.–Mineral.) in 1937 without the official defense procedure (and even without the university diploma). He was one of the youngest and active participants of the International Geological Congress held in Moscow in 1937, when he pioneered in demonstrating new paleogeographic maps having a bearing on the geological history of this country.

At the end of 1930s, Yanshin joined the Moscow Society of Naturalists, the oldest scientific society of Russia. He has never been its formal member, even when had moved in Novosibirsk for many years. He always was the life of the society and had been its vice president and president for the last 40 years.

It was also in 1930s, when he became involved in publishing geological journals and books. Being fond of a book since his childhood and knowing it excellently from a manuscript and printing machine to a final copy still keeping a smell of inks, he was a wonderful bibliophile obsessed by a charm of well-published books for all his life. His work in the Editorial and Publishing Board of the Academy of Sciences could not but impressed everybody by the vivid activity. Some book

series issued under his supervision, such as *Scientific Biographical Literature* (more than 550 books) or the last series *The Heritage of V.I. Vernadsky* issued in many volumes, can be regarded as a scientific feat. His wonderful ability to select persons holding the same views and devoted to the deed of publishing must always be kept in mind.

In pre-war, war and post-war years, Yanshin had to give much attention to the geology of different mineral resources, to organization of pertinent studies and geological institutions, and to be sure, to participation in routine field works. One such work nearly ended with a catastrophe and had serious repercussions for all his life. When studying one of the prospect pits in the Aral region, he fell with a tub down from the pit mouth to the pit face at a depth of 24 meters. Serious leg fractures, breakage of a heel bone, the direct danger of leg amputation, and the acquired traumatic diabetes required a long hospitalization. His organism, mighty by nature, was not only capable to cope with such a shock, but allowed him to make the best use of a "spare" time in hospital: he took up translating geological papers from French and wrote a unique monograph *Geology of Northern Aral Region* (the size of edition is 74 printer's sheets), which he defended as his doctoral dissertation on December 18, 1952. That was a real labor exploit. I know this classical work very well and believe that this book exactly completes a series of greatest geological and geographical works of the 20th century. It seems natural that Yanshin was awarded the A.P. Karpinsky Prize for this outstanding work in 1953.

In the Geological Institute, the USSR Academy of Sciences, Yanshin took charge of the Laboratory of Regional Tectonics and continued directing it when he moved to the Siberian Division of the Academy for a persistent work. By the moment of setting up the division (1957–1958), his authority among geologists was so high that Academician N.S. Shatsky immediately nominated Aleksandr Leonidovich to fill a vacancy of the academy member, which was specially opened in this new regional division. It was uncommon practice, but Shatsky was sure that he had not put his disciple in the danger of not being elected. Yanshin was elected Member of the Academy on March 28, 1958, i.e., at the date of his birthday, thus passing one more step in his academic carrier.

The Siberian period of Yanshin's activity lasted for about a quarter of the century. His extensive knowledge in all spheres of the Earth's science appeared to be most wanted. An eminent geologist and geographer, he happened to be a competent geophysicist, geochemist, pedologist, hydrologist; he joined the community of biologists as an ardent opponent of Academician T.D. Lysenko. In the young division headed by Academician M.A. Lavrent'ev in the east of Russia, it was hard to find a person more suitable for that vacancy than Yanshin because of his outstanding erudition, the ability to work hard and to respond willingly to all organizational actions. He immediately filled the post of vice director at the Institute of Geology and Geophysics created by Academician A.A. Trofimuk and took charge of the Division of Geological Sciences (now it is a special institute) with many departments, large laboratories, and research groups. The departure from Moscow was not easy but painful; Yanshin has retained all his relationships—scientific, publishing, social—and continued directing his laboratory at the Geological Institute (GIN) and heading the Editorial and Publishing Board of the Academy at all plenary meetings. But even such a mighty person like Yanshin could not cope with an excess stress and constant change of time zones without rest, and he sometimes experienced a dangerous coma. Only when he got married to Fidan Taufikovna, his health was put under a strict control. It is hard to overestimate her credits in this respect and experienced assistance.

The surprising thing of this busy period is that Yanshin took charge of a new, original, long planned project "Tectonic Map of Eurasia" (scale 1 : 5000000) accompanied by a fundamental monograph. This work seems to occupy the most significant place among all his works. He was awarded the first State Prize of the USSR in 1969. Nine years later (1978), he got next prize of the state for editing the 15-volume monograph "The Relief History in Siberia and the Far East."

It is hard to find a branch of geology, where Yanshin felt himself cheerless, but some of them attracted his attention immensely. These are the regional and general tectonics, relationships between tectonic and sedimentary process, volcanism and sedimentation in the context of the tectonic and climatic evolution, distribution patterns of mineral resources in ancient sedimentary basins, recent tectonic movements and eustatic fluctuations in the World Ocean, and undoubtedly, the general tectonic evolution of the Earth, especially since the time (1968) when deep sea drilling brought abundant new data on the ocean floor geology. His personal contribution to study of young platform structures, salt-producing and phosphate-bearing basins, and areas of hydrocarbon concentration in the Earth's crust was especially great. For sake of science, he visited a plenty of countries, worked in all continents and distant ocean areas, headed tens of research groups, left hundreds of followers and disciples in different countries (Mongolia, India, China, Germany, North Africa, Mediterranean countries, etc.).

It happened so that after the tragic accident with Academician A.V. Sidorenko in Algeria in 1982, Yanshin had to return to Moscow to took charge of the Institute of Lithosphere (now the Institute of Lithosphere of Marginal Seas, RAS), and to be elected Vice President of the USSR Academy of Sciences in September 1982. As he was never separated in his research and organizational activity from the academy heart, it took no time for him to adjust himself to the new high post: he has got under official control what he knew well long ago as a scientist. Meanwhile, time intro-

duced corrections in the general trend of the Earth science development, and geological survey of this country was at the threshold of next restructuring.

He had to struggle in Siberia with the state machinery and governmental departments for protection of the environment and natural resources, a thoughtless and spendthrift attitude to which had acquired traits of nearly a colonial policy. The Siberian Division headed by Academician A.A Trofimuk, as well as scientists who shared similar opinions (Yanshin undoubtedly was among them) desperately fought against such a policy. I should mention here the struggle to protect the unique Lake Baikal with its 20% of world reserves of fresh water and against the turn of some Siberian rivers in order to get a warming effect in the south for the sake of "gold" tomato, as well as the appropriation of mineral deposits, the properties of the state, by local administrations. As early as in 1988, the worried Academy elaborated a multipurpose program of biospheric and ecological studies and recreated an abate activity of the Scientific Council on Biosphere Problems of the Russian Academy of Sciences under guidance of Yanshin. Exceptionally active in this respect were prematurely deceased Academician V.A. Koptyug and Academician N.P. Laverov who took charge of the Federal Program "Global Changes in the Environment and Climate" that gained a wide recognition in the world. Yanshin commenced all these studies, which required a tremendous persistence and courage. His relentless struggle with such an anti-ecological monster as the Ministry of Water Management was uncompromising; owing to his personality many first-class specialists joined him in this deed that prevented a series of ecological catastrophes in the country.

Being a successive propagandist of Vernadsky's ideas on the unavoidable biosphere transition to the noosphere stage of evolution, Yanshin focused upon this most urgent problem during his later years. His successful activity in this sphere resulted in publication of collected works by Vernadsky, the wonderful naturalist, prophet, and thinker. A further development of these ideas and their practical realization is the main testament left for us by Yanshin. No more comprehensive concept of the cosmic and humanitarian aspect, like the notion of the biosphere, was created in the 20th century. It synthesizes scientific ideas on global ecology in the Earth's past, the protection program of our planet, the unique creation of the Universe, and the modern philosophical substantiation of the human society evolution. Yanshin is often called now "a man of the noosphere." It is a very fine metaphor, but he was not actually, as the noosphere is still a long way ahead from now, and we come to this conclusion every day. But the deep faith of Vernadsky and Yanshin in the sphere of sense and future harmony of the World will stay with us. Let it sound as an ardent call of scientists who were given the ability to see ways to the noosphere. May be these are the truly ways of creative persons.

B.S. Sokolov

Aleksandr Leonidovich Yanshin was a real Scientist and Geologist. The area of his scientific interests involved many geological disciplines, including the study of mineral resources, primarily of sedimentary phosphorite, bauxite, salt, iron ore, oil and gas deposits. During most of his scientific activity, stratigraphy and tectonics have been a center of his preoccupation, especially tectonics, and only during past decades these were forced out by ecological problems due to their increased importance for the modern society. For this reason and because of my own specialization, I will dwell here on tectonic works of Yanshin.

Yanshin began his field studies in the western slope of the extreme southern edge of the Urals, in the so-called Kargala Mountains to which the first tectonic work of Yanshin was devoted. The work was published in 1932 when he was 21 year old! Yanshin recognized here manifestations of thrust tectonics and showed that it is typical of the whole belt from the Polar Urals, where the same conclusion has been already done by K.G Voinovskii-Kriger and V.A. Varsanof'eva, to the extreme south of the Urals. Later, after revealing the Triassic deposits in the region, Yanshin pioneered in proving a much younger age of thrust faults in the Urals, which affected these deposits as well.

Later, his study extended for a vast territory of the southern plunging area of the Urals and Aral region. The work resulted in inferences of fundamental importance. He found out that structures of the Mesozoic–Cenozoic cover of the region inherited dislocations of the Paleozoic basement, this opened a possibility to trace a buried extension of the Uralian system far southwards to the Aral region. Yanshin reported his results at the First Tectonic Conference in 1948, and it became apparent for all participants that a new bright and talented expert in tectonics had appeared (Yanshin was 37 years old at that time).

A fundamental monograph by Yanshin (731 text pages and three printer's sheets of appendices) on geology of northern Aral region was published in 1952. This work is an example of a regional monograph unsurpassed to date. Problems of the geology of the region were comprehensively considered, among them important tectonic and stratigraphic discoveries made by Yanshin.

Investigation of structural features of the Aral region was a starting point for him to study tectonics of the whole Turan Platform and young platforms of Eurasia. Young colleagues, first of all R.G. Garetskii (now vice president of the Belarus Academy of Sciences and a foreign member of the Russian Academy of Sciences), A.E. Shlezinger (now chief scientist at the Geological Institute, RAS) actively assisted Yanshin in solving these problems. As a matter of fact, Yanshin and his school elaborated a doctrine on young platforms, which is similar to that created by Shatsky on older platforms. Later, Yanshin also paid much attention to the Caspian depression, a major and peculiar structure of the East

European platform that borders the South Urals and the Turan plate, main subjects of his investigation. He was especially interested in two problems related to that depression: the accumulation of a huge salt mass that is untypical of normal shallow-water basin, and the structure and accumulation history of subsalt deposits, in which appreciable oil-and-gas reserves were revealed later. Yanshin was first to prove that a deep-water basin existed there in the pre-Kungurian time.

Yanshin, the best expert on geology of the vast territory of the Caspian region, South Urals, and Turan plate, was invited by Shatsky for collaborative work on two tectonic maps of the Soviet Union, which were published in 1954 and 1956, and on the International Tectonic Map of Europe, published in 1964.

The international recognition of the two maps inspired Yanshin to compile the Tectonic Map of Eurasia, the largest continent of our planet (scale 1 : 5000000). It was a very hard task as some regions of Asia, such as Tibet, were poorly studied. Nevertheless, the team headed by Yanshin was able to cope with the problem posed, and the map published in 1966 has not lost its importance until present despite a tremendous flow of new actual data. Nothing of that kind has ever been compiled, as the International Tectonic Map of Asia is still in work.

Among problems concerning the tectonics of Asia, an important one deals with the nature of orogeny that affected Central Asia in geologically recent Oligocene–Quaternary time within the area evolved for a long time under the quiet platform regime. The work on that problem gave rise to a new idea of the epiplatform orogeny that was formulated by S.S. Shul'tz and A.L. Yanshin in a special paper on the issue (it is often termed now the intracontinental orogeny). In his reports and publications, Yanshin dwelt as well on the problem of median masses in foldbelts.

It should be emphasized that Yanshin, hand in hand with A.V. Peive, took an active part, since the early 1960s, in reanimation of the notion that postulates a large role of horizontal movements, particularly of thrust and strike-slip faults, in structural development of the Earth's crust. This idea had been neglected for a long time previously, while preference was given to vertical movements. In his earliest tectonic work, Yanshin has already substantiated the existence of thrust faults in the South Urals!

Actively supporting ideas of mobilism, which gained the recognition in this country with great difficulties, Yanshin held a special view on the origin of deep basins of the Black and Mediterranean seas, as well as on development of marginal seas of the Far East. This view is expressed in a series of works written in collaboration with A.E. Shlezinger and E.V. Artyushkov. At the same time, he was the editor of the first large-scale tectonic map of northern Eurasia based on the above ideas. A lot of the credit must go to Yanshin for disproving the viewpoint, which predominated in 1940s–1950s and implied that shallow-water marine deposits absolutely prevailed in sedimentary sequences of the geological past. Such a viewpoint allowed researchers to apply unconditionally and everywhere the method of the thickness analysis, which followed the statement that the thickness of sediments always corresponded to the extent of tectonic subsidence. In the work published in cooperation with Garetskii, Yanshin showed that the widespread subsidence events are incompletely compensated by sedimentation, and the thickness could not rightly reflect the scale of subsidence. Their inference concerns not only foldbelts, but platforms as well (the Caspian depression!).

Yanshin also criticized another, rather popular idea on global transgressions and regressions, and pointed to a series of contradicting facts. At present, when Vail's curve has received the ample recognition, his critics is quite appropriate, as it means that the impact of regional tectonics at the level of sedimentation surface should be taken into account even within the passive continental margins.

In some presentations and publications, Yanshin pointed out the scantiness of the actualism (if we understand it as a synonym of uniformitarianism). He also consecutively advocated and popularized the importance of the idea that suggests evolution of all geological processes throughout the Earth's history. He made the problem to be included into the list of the key problems of the Earth sciences and worked on the issue with regard to evolution of sedimentation and sedimentary formations of the Phanerozoic and Precambrian.

Yanshin was the first to assess new advantages offered to geology and, particularly, to tectonics by the remote sensing from the space.

As an initiator and permanent head of the Soviet–Mongolian Expedition, Yanshin placed particular emphasis upon the geology, particularly tectonics and metallogeny of that very interesting country.

When reading a long list of Yanshin's publications, one unwittingly pays attention to three aspects: first, to unusually wide scientific interests; second, to a constant returning (each time at the level of new knowledge and ideas) to some pet subjects (the Caspian region, Turan plate, Asia as a whole, young platforms, deep-water basins); third, to unfailing aspiration of solving practical problems, particularly those concerning phosphorites (his first love), potash salt, oil, and gas. Interests of Aleksandr Leonidovich gradually shifted towards the Vernadsky's ideas of biosphere and noosphere. He became enthusiastic about ecology, but never forgot geology and tectonics, the great "master" of which he remained.

V.E. Khain

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